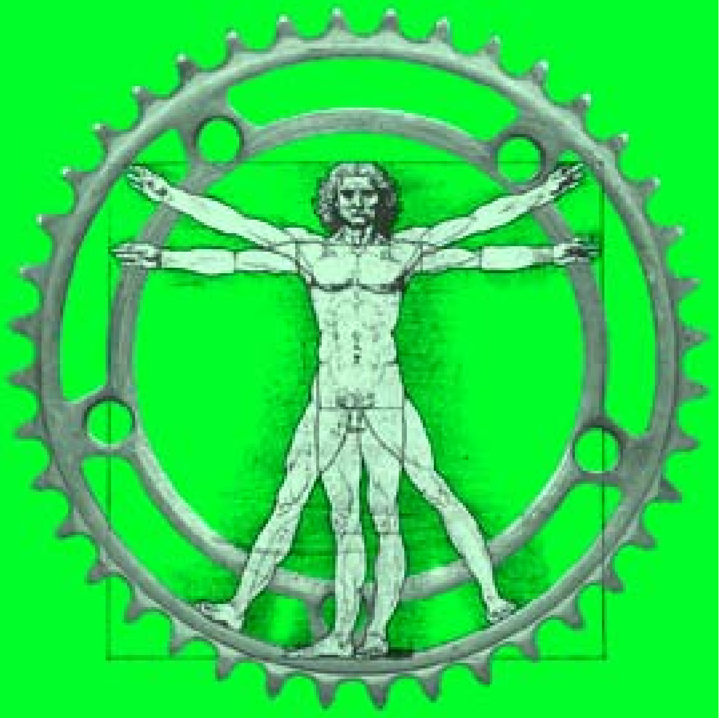

# HUMAN POWER

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### *NUMBER 54 SPRING 2003*

**Editorials**

**Articles**

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## FROM THE EDITOR

### Farewells

This issue of *Human Power* is long overdue. We have problems and transitions in *Human Power*, the HPVA, the IHPVA, and in the world. I must note a number of farewells:

The German HPV chairman Ralf Wellmann died of his own will amid the preparations for the next HPV World Championships in Friedrichshafen, and deeply shocked those of us who knew him. Steve Donaldson, secretary of the British Human Power Club, was in collision with a car while cycling through Bucksburn, Scotland. He died in hospital. Steve was a familiar competitor at international championships, and active in the IHPVA. We all miss these two young men greatly.

We also sadly note the passing of Gene Larrabee, who was one of the first to show how to design really efficient propellers suitable for record-breaking, human-powered airplanes and hydrofoils. Known as "Professor Propeller", Gene furnished his courses with attractive and clear illustrations. In this issue we publish a series of these, with captions, as a commemorative article on minimum induced loss wings and propellers, preceded by an obituary.

### Also in this issue

*Human Power* is lucky to be able to include extracts from *Bicycling Science III* which is being published in early 2004, written by our own Dave Wilson (with contributions by Jim Papadopoulos elsewhere in the book). We include a chapter on aerodynamics which presents an easy way of incorporating Reynolds-number effects, and part of a chapter on unusual and future HPVs.

Danny Too's article on the biomechanics of HPVs systematically lists the factors affecting human-powered propulsion with emphasis of the biomechanical aspects.

Finally, we have an article by J.P. Modak and A.R. Bapat which has been in the pipeline for some years and appears here at last in a condensed version. It describes an investigation of a human-powered flywheel motor and attempts to create mathematical models for this.

### Transitions

*Human Power* itself is in transition. This is the last issue John "Elrey" Stephens helped produce, as he is moving on to a new venture soon, and also because *Human Power* and *HPV News* do not yet conform to a sustainable business model for which we have lobbied. As a print professional Elrey helped to improve the quality of *Human Power* in the last few years, for which we are very grateful. *Human Power* readers can expect one or two more issues in the present style, but in 2004 there will have to be some changes.

The IHPVA has a new chairman, Richard Ballantine, who is striving to change the present status of an "international agreement" into a more formal and professional legal form. One of the benefits of this would be that the responsibility for the physical production of *Human Power* could be transferred from the HPVA to the IHPVA and also allow increasing our readership.

Richard, besides being a successful author and publisher of bicycle media, is like many of us a "political cyclist" and writes briefly about the connection between HPVs and the war on Iraq.

## COMMENTARY

*The editorial views expressed in Human Power are those of the authors and do not neccessarily coincide with those of the board and officers of the HPVA.*

In this war on Iraq, we have a number of casualties (as of May/June 2003): 5500 to 7200 Iraqi civilians, 5000 to 50,000 Iraqi soldiers, about 200 US/UK soldiers, and about ten journalists (http://www.iraqbodycount.net/). When I started writing this editorial, bombs and missiles were raining down upon Mesopotamia, this ancient land between the Tigris and Euphrates rivers, the cradle of human civilisation. The present population, trapped between the plans of a barbaric dictatorship and a group of ruthless businessmen, paid a heavy price for living on top of large deposits of oil. That the war has much to do with oil is evident, as after replacing the dictator, the businessmen ordered the oil wells and the oil ministry to be well-guarded while allowing the world-famous national museum and library to be looted and the hospitals and food stores ransacked. Some of humanity's oldest written records, clay tablets from the age-old monuments of the area, describe how rulers went to war in order to gain strategic positions and natural resources, justifying their rapes in the names of gods. Thousands of years later this is still so; it appears we have progressed no further than then.

The relatively modern accomplishment called democracy seems to have failed. Something is fundamentally wrong when a few men are able to launch wars against the wishes of the overwhelming majority of the world's population, governments and churches. This war has divided friends, united foes, and accomplished the opposite of what its proponents claim. The businessmen have weakened the only legal world government, the United Nations, and are attempting to erect a kind of military-economic empire, to be defended by new technology—including a new generation of nuclear weapons. All this generates hateful anti-western feelings and terrorism is increasing daily.

Eccles

What has this to do with "Human Power"? The main reason is the strong connection with oil. Oil is cheap in terms of money, but commands a heavy price in terms of human life. This is not new, there have been other oil wars with far more deaths and misery. What is new is the audacity with which our fragile hard-earned progress of human civilisation and achievements such as human rights, democracy, freedom and justice are being eroded by our sinister characteristics such as fear, greed, and fundamentalism. The Charter of the United Nations and associated works of International Law have been transgressed. Lies and deceptions abound. The land of the free is becoming the land of the fearful. Never before have the dystopias predicted by Orwell and Huxley gotten so close to reality.

The human principle of "right" has yet again succumbed to the animal principle of "might". Is all then lost? Are we doomed to remain prisoners of our archaic instincts, to be animals forever? I do not think so. Never before has the whole world been able to debate a war before it happened. Never before has there been such universal worldwide democratic participation with so many millions of people demonstrating in the streets or with their voices, pens and keyboards. Never before have the United Nations denounced a war of aggression so clearly. The action of the present U.S. government and its vassals is a large setback, but not the end. Thanks to modern communications and independent media, disinformation and propaganda can be unveiled more quickly and anybody capable of logical thought can separate truths and untruths. The new information society is fighting back. The key to future peace is literacy. For example, people who read the classic *Animal Farm* by George Orwell may find out why our rulers employ soldiers and fire teachers, and how they subtly control us with methods more effective than censorship. As global awareness increases we may be heading for a new Renaissance and be able to escape the presently rather dark ages together. At some point we will become true humans.

*—Theo Schmidt*

## THE POLITICS OF HUMAN POWERED VEHICLES

### Richard Ballantine

*Richard Ballantine, chair of the IHPVA and of the British Human Power Club, writes on the connection between HPVs and the Iraqi War.*

Citizens in developed countries enjoy high living standards: plenty of food and water, advanced health care, and abundant availability of consumer services and goods. Citizens in "developing" countries do not—and cannot. As Edmund Wilson notes in his marvellous and utterly engaging new book, *The Future of Life*,[1] raising living standards in developing countries to the same level as developed countries would require the resources of a planet five times the size of Earth.

Withdrawals from nature's bank are already running deeply in the red. Fossil fuels, water, fish, timber, land, and other vital resources are being depleted faster than they can be renewed. Crucially, a minority of the world's population, something over one thousand million people, account for about 80 per cent of consumption. The majority, about five thousand million people, get by on what is left, and of this group, about one thousand million do not have enough food and water to sustain life.

The problem in want is not scarcity. There is enough to go around. The problem is that too few people have too much. Perpetuating this status quo is the root cause of wars, internal conflicts within countries, destabilized societies and governments, and support for repressive regimes.

The war in Iraq is about black gold—the last significant reserves of oil. Once Iraq is conquered, the coalition forces intend to take the oil to pay for the costs of the war, establishing a new regime, and rebuilding the country. The oil will go to developed countries and be used to fuel motor vehicles.

As every reader of *Human Power* knows, the majority of journeys are short and local, and can be accomplished most efficiently by cycling. Standard upright bikes are great, but HPVs are better; faster, safer, and more comfortable. They are also practical for transporting freight.

The politics of HPVs are simple. In developed countries, HPVs can meet a large proportion of transport requirements, and in so doing, reduce consumption of petroleum. The decrease in size of environmental footprint in terms of resource depletion means less incentive for taking oil through economic and military force. As well, there is less damage to the environment and human health from pollution.

Finally, and not least, HPVs suit modern demographic trends. The population of the world is increasing, and at the same time, more and more people are living in cities. In high density urban environments, where space is limited, bikes and HPVs are not just hugely more energy-efficient than motor vehicles, they are also faster.

Bombs and cars go together—and in the end, HPVs will beat both.

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[1] Wilson, Edward O. 2002. *The future of life.* NY: Alfred A. Knopf. ISBN: 0-679-45078-5

# HPV science

***by David Gordon (Dave) Wilson***

*Editor's note: Human Power* is able to include extracts from *Bicycling Science III*, which will be published in early 2004, written by our own Dave Wilson (with contributions by Jim Papadopoulos elsewhere in the book).

We include a chapter on aerodynamics which presents an easy way of incorporating Reynolds-number effects, and part of a chapter on unusual and future HPVs.

## Summary

The following is a collection of extracts relevant to HPVs from three chapters of the third edition of *Bicycling Science*: from those on aerodynamics, on unusual pedaled machines, and on HPVs in the future. Readers of, and contributors to, *Human Power* have been loyal users of the second edition of *Bicycling Science*, and we have chosen some topics that have been substantially updated in the hope that they will be useful. (The MIT Press plans to publish the third edition sometime in 2003.)

Two of the new topics in the aerodynamics chapter are a clarification of the two principal alternative definitions of the drag coefficient, and a simplified method of calculating the Reynolds number, which influences the drag, sometimes dramatically.

## Drag coefficients

One aim of aerodynamic experiments on an object is to measure its drag coefficient, $C_D$, defined as the non-dimensional quantity

$C_D \equiv \text{drag}/[\text{area}\cdot(\text{dynamic pressure})]$ *(Eq. 1)*

The drag is the force in the direction of the relative flow (or of the dynamic pressure). The area A and its related drag coefficient $C_D$ are defined later. The product $C_D \cdot A$ (in the same units as A) is a very useful number in studies of the drag of bodies. The drag is simply the product $C_D \cdot A$ times the dynamic pressure. We list this product later (in table 1) for some types of HPVs.

The dynamic pressure is the maximum pressure that can be exerted by a flowing stream on a body that forces it to come to rest. At speeds that are low relative to the speed of sound (say, below 45 m/s or 100 mile/h), the dynamic pressure is closely approximated by:

$$\text{Dynamic pressure} \approx \left(\frac{\rho \cdot V^2}{2 \cdot g_c}\right) \quad \textit{(Eq. 2)}$$

in which (for SI units) ρ is the air density in kg/m$^3$, and V is the velocity of the air in m/s. The constant $g_c = 1.0$ for SI unit systems. It is found in Newton's law of motion $F = m\ a/g_c$ where F is in newtons, N, m is in kg, and a in m/s$^2$ In U.S. units, $g_c$ has the value 32.174 lbm-ft/lbf-s$^2$ when the equation relates m in pounds mass, F in pounds force, and acceleration a in ft/s$^2$. The dynamic pressure *vs*. velocity and altitude is given in figure 1. At the time of writing, the HPV speed record was about 35 m/s and was set at an altitude of between 2500 and 3000m, and it can be seen that the dynamic pressure would have been over 600 N/m$^2$ (0.087 lbf/sq.in.).

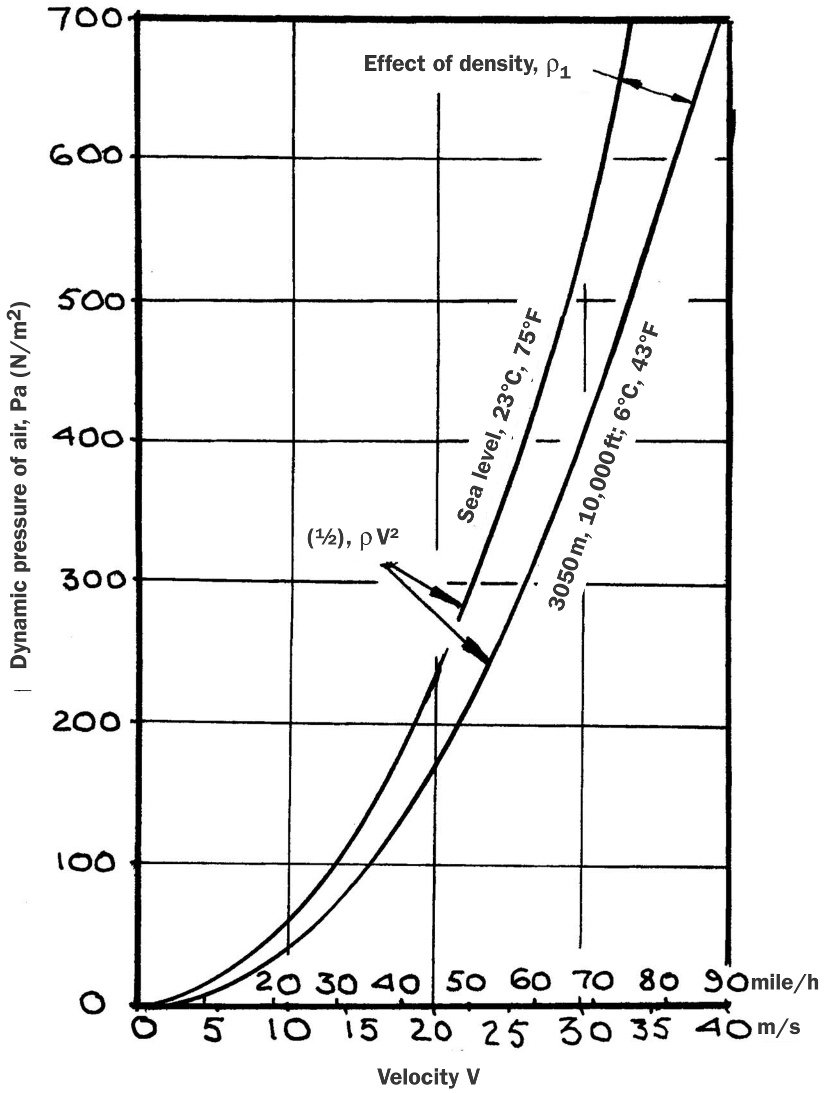


**Fig. 1. Dynamic pressure of air *vs.* velocity and altitude**

## Different definitions of area and of drag coefficient

The area can be defined in several ways, each one leading to a different definition and a different value of the drag coefficient $C_D$. The usual definition is the frontal area, and unless otherwise stated, this is the form of drag coefficient we will use.

Thus, the drag force is given by

*(Equation 3)*

Another form of drag coefficient is defined in terms of the surface area of the body, and is used only for slender and/or streamlined bodies, where the drag is primarily from skin or surface friction, rather than from the eddies coming from bluff bodies. Here we give this form the subscript "SA", and is defined as:

*(Equation 4)*

For a given body at a given condition, the surface-area coefficient of drag is smaller than the frontal-area coefficient because the surface area is larger than the frontal area. For a sphere the area ratio is 4.0. For a long cylinder of diameter D and with spherical ends the ratio is $4 \cdot (1 + L/D)$, where L is the length of the straight portion of the cylinder. The measured value of $C_D$ for a rounded-end cylinder aligned with the flow increases with L/D, whereas the value of $C_{D,SA}$ decreases with L/D to compensate for the increasing surface area (fig. 2).

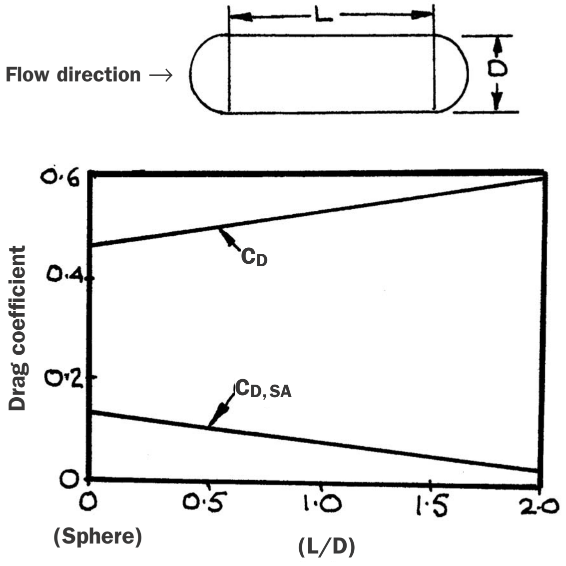


**Figure 2. $C_D$ and $C_{D,SA}$ for a circular cylinder**

$$\text{Drag} = C_D \cdot (\text{frontal area}) \cdot (\text{dynamic pressure}) \quad \textit{(Eq. 3)}$$

$$C_{D,SA} \equiv \frac{\text{drag}}{(\text{surface area}) \cdot (\text{dynamic pressure})} \quad \textit{(Eq. 4)}$$

$$\dot{W} = (\text{drag force}) \cdot (\text{relative vehicle velocity}) \quad \textit{(Eq. 5)}$$

$$\text{Power, watts} = (\text{drag force, newtons}) \cdot (\text{vehicle velocity, m/s}) \quad \textit{(Eq. 6)}$$

$$\dot{W}(\text{hp}) = \frac{\text{drag}(\text{lbf}) \cdot \text{velocity}(\text{ft/s})}{550((\text{ft}-\text{lbf/s})/\text{hp})} = \frac{\text{drag}(\text{lbf}) \cdot \text{velocity}(\text{mile/h})}{375((\text{mile}-\text{lbf/h})/\text{hp})} \quad \textit{(Eq. 7)}$$

The significance of not confusing these two definitions can be illustrated by the following anecdote. In the early days of the quest for the Du Pont Speed Prize for the first human-powered vehicle to reach 29 m/s, 65 mile/h, an MIT student decided that he could win the prize by assembling many pedalers in a line within the same frontal area as one pedaler. He had found that the drag coefficient for a reasonably streamlined single-rider recumbent vehicle was 0.15 and that the frontal area could be below 0.5 m$^2$. He calculated the drag at 29 m/s to be about 38 N, leading to a power required to overcome air drag alone at over 1100 W. He decided to build a vehicle carrying ten to fifteen riders in a line, because the frontal area would be the same, therefore (he thought) the drag would be the same, and the air-drag power required from each of ten riders would be an easily-manageable 110 W. He confidently forecast reaching 80 mi/h, 36 m/s.

For various reasons that plagued development the vehicle was quite slow. But the fallacy behind the designer's reasoning was that the drag coefficient based on frontal area would not increase as the vehicle was made longer. It would and did, probably quadrupling the drag of a one-person faired body of the same frontal area. It is often preferable when calculating the drag of a streamlined body, therefore, to use the drag coefficient based on surface area. However, either form may be used with confidence so long as the value found experimentally for one configuration is not applied to the analysis of a completely different shape.

The propulsion power, $\dot{W}$, necessary to overcome drag is

*(Equation 5)*

(We use W as a symbol for quantity of work, such as joules or ft-lbf, and $\dot{W}$ for the rate of doing work, which is power, in watts or ft-lbf/s or horsepower.)

Since the drag force is approximately proportional to the square of the velocity, the power to overcome drag is approximately proportional to the cube of the velocity.

Only in still air is the vehicle velocity the same as the relative velocity used to calculate the drag force. When there is a headwind or a tailwind, the relative velocity is different from the vehicle velocity.

In SI units the relationship is

*(Equation 6)*

If the drag is measured in pounds force and the velocity is given in feet per second, the power is in ft-lbf/s. This may be converted to horsepower by dividing by 550 (1 hp = 550 ft-lbf/s); or miles per hour (1 hp = 375 mile-lbf/h) may be used:

*(Equation 7)*

$$\text{Reynolds number, } Re \equiv \frac{(\text{air density}) \cdot (\text{relative air velocity}) \cdot (\text{a length})}{\text{air viscosity}} \qquad (Eq.\ 8)$$

$$Re = \frac{2}{3}(\text{sphere diameter, m}) \cdot (\text{relative velocity, m/s}) \cdot 10^5 \qquad (Eq.\ 9)$$

$$\rho = \frac{\text{pressure in pascals}}{286.96 \cdot \text{temperature in kelvin}} \qquad (Eq.\ 10)$$

$$Re = \frac{\rho \cdot V \cdot L}{R \cdot \mu \cdot T} \qquad (Eq.\ 11)$$

## Drag

For any one shape of body, the variable that controls the drag coefficient is the (dimensionless) Reynolds number, defined in general as

*(Equation 8)*

where the length has to be specified for each configuration. For a sphere and for a circular cylinder in flow transverse to the cylinder axis the specified length is the diameter. (One states "the Reynolds number based on diameter".) For streamlined bodies the length in the flow direction is more usually specified. This length for an aircraft wing is called the "chord". The specified length in bodies like streamlined fairings is more usually the actual length.

For a sphere moving in air at sea-level pressure and 65 °F (19 °C), this becomes approximately

*(Equation 9)*

A more general method of determining the Reynolds number for any pressure and temperature is shown in figure 3. Air density is a function of pressure and temperature:

*(Equation 10)*

where the factor in the denominator is R, the "gas constant" for air, 286.96 J/kg-deg.K. The air pressure can be obtained from the local weather office—but it is always given for mean sea level, and may need converting for the altitude required by using, for instance, the standard-atmosphere curve of figure 4. (The pressure variation with altitude in fig. 4 would be useful everywhere on earth; the temperature would vary considerably.) The pressure will probably not be given in pascals (N/m$^2$), and may be converted using an appropriate part of the following:

1 bar = $10^5$ Pa = 0.9869 atm = 14.5038 lbf/sq.in. = 750.062 mm Hg = 29.530 in. Hg.

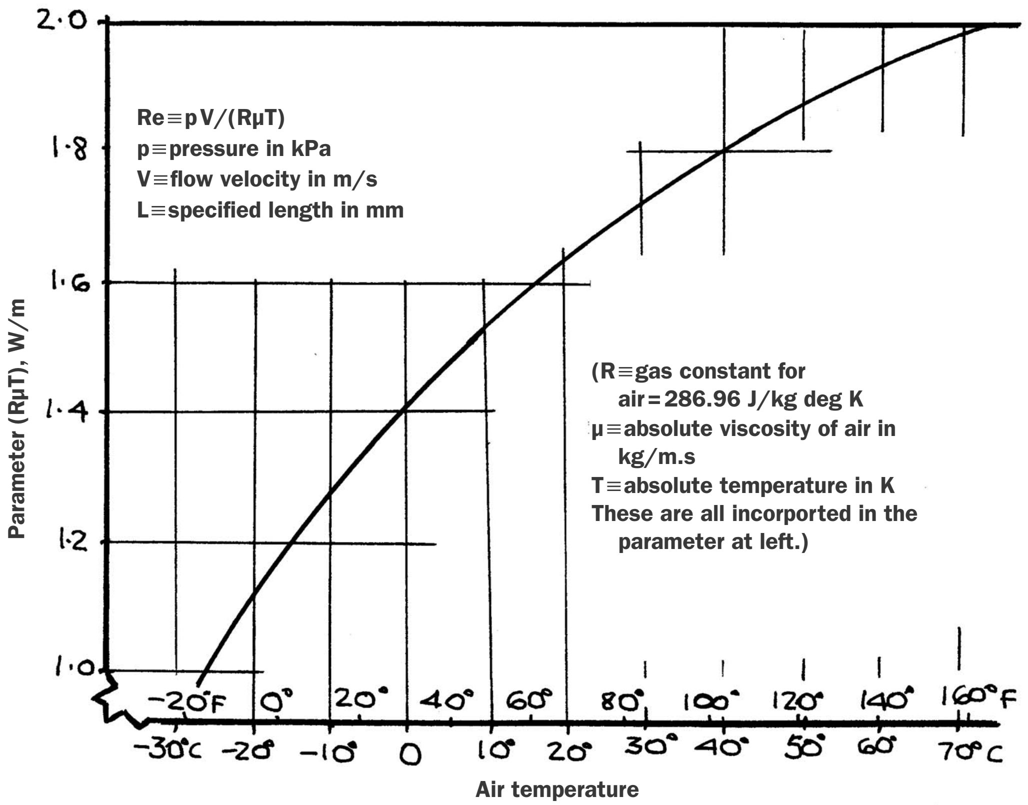
The temperature in kelvin is the temperature in celsius +273.15. Sea-level air density is about 1.2 kg/m$^3$ at 16 °C or 60 °F and about 1.14 kg/m$^3$. at 38 °C, 100 °F for dry conditions. If the humidity is 100%, the density at the cooler of these temperatures drops by about 1%, and by about 2.5% at the hotter temperature.

However, it is not strictly necessary to calculate the air density purely to determine the Reynolds number. Since both the density and the air viscosity are functions of temperature, the parameter R · μ · T is just a function of temperature, where μ is the "absolute" viscosity of air in kg/m.s., and T is the "absolute" temperature in degrees kelvin. The Reynolds number can then be found from the pressure, temperature, velocity and length alone:

*(Equation 11)*

where the denominator is the parameter plotted as a function of temperature only in figure 3. An example of the use of these charts follows.

Figure 3. Reynolds-number parameter for air



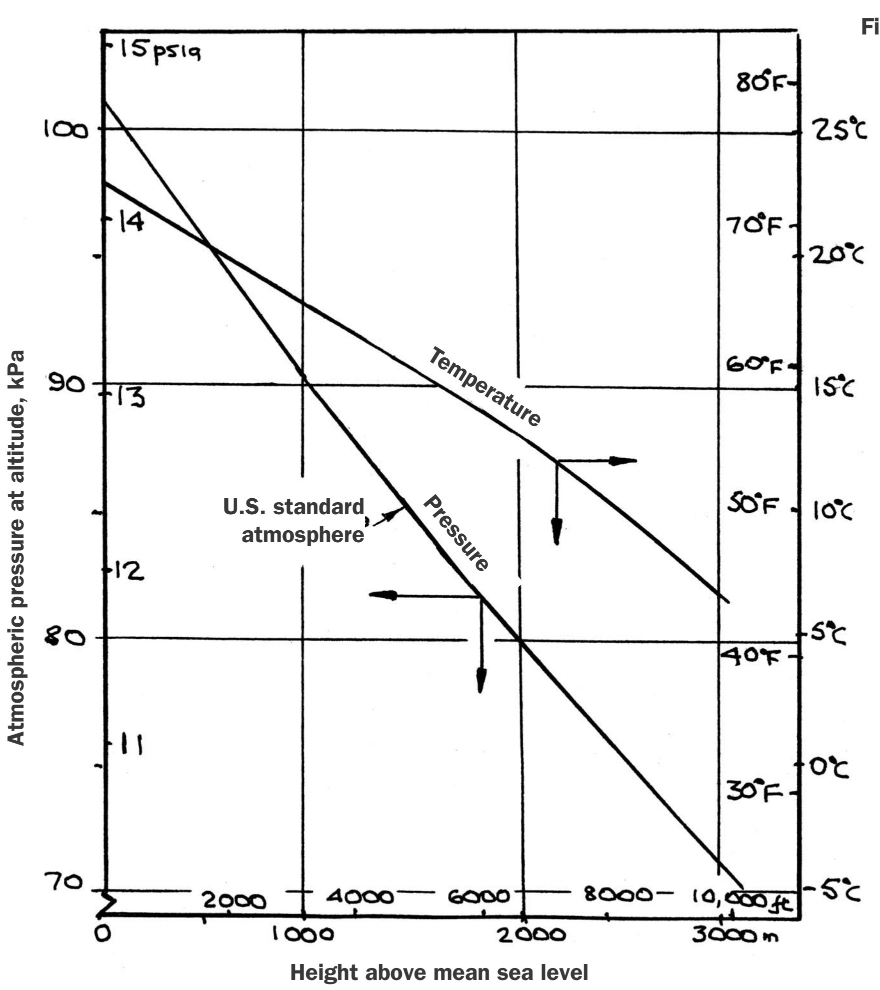


Figure 4. U.S. standard atmosphere (plotted from U.S. Government data)

### Example

**Find the Reynolds number for air at 20 °C, sea-level pressure (110 kPa), flowing past a cylinder 200-mm diameter at 10 m/s.**

**At 20 °C the parameter R · μ · T is 1.64 (fig. 3). Therefore**

**Re = 110,000 × 10 × 200/(1000 × 1.64) = 1.34 × $10^5$**

## Coefficient of drag vs. Reynolds number for various bodies

The drag coefficients of various bodies versus Reynolds number have been plotted in figure 5.

It can be seen that at Reynolds numbers over 3 × $10^5$, even smooth spheres do not need trip wires or rough surfaces because a laminar boundary layer will spontaneously become turbulent under these conditions. When the boundary layer becomes turbulent at increased velocity and Reynolds number, the drag coefficient falls sharply from 0.47 to 0.10. (The drop in drag coefficient with increase of velocity or Reynolds number is not usually rapid enough to counteract the need for greater propulsion power, increasing as it does with the cube of velocity. However, hypothetically, certain bodies in certain conditions where a very rapid reduction in drag coefficient is experienced as the relative velocity V is increased could, theoretically, achieve an increase in speed of 20–30% without any increase in power.) A golf ball about 40 mm in diameter driven at an initial velocity of 75 m/s has a Reynolds number of 2 × $10^5$ at the start, and would be in the high-drag-coefficient region if it were smooth. The dimpling shifts the "transition" point to lower Reynolds numbers and gives a low $C_D$. Thus, paradoxically, a rough surface can lead to low drag.

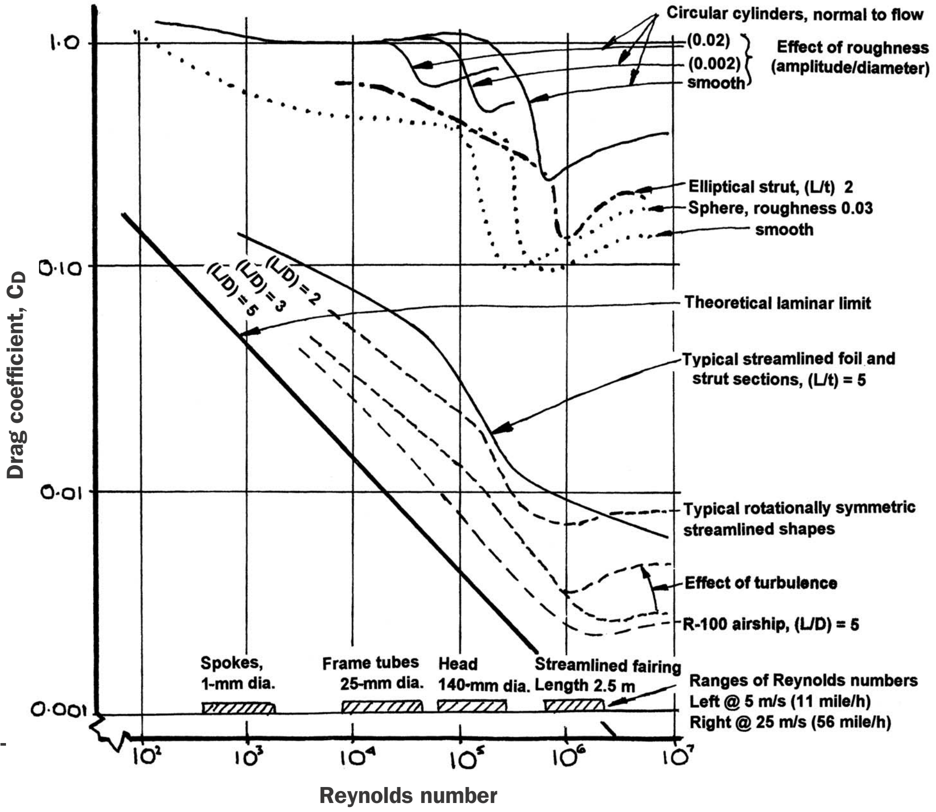


Figure 5. Drag coefficient *vs.* Reynolds number for useful shapes (plotted from data from Hoerner [2], and other sources)

**Table 1. Bicycle drag coefficients and other data**[1]

| Machine and rider | Drag coeff. on frontal area, $c_D$ | Frontal area | | $C_DA$ | Power to overcome air drag at 10 m/s (22 mi/h) watts | Power to overcome rolling resistance AT 10 m/s for specified total mass, kg, and $C_R$ value | | |
|---|---|---|---|---|---|---|---|---|
| | $C_D$ | $m^2$ | $ft^2$ | $m^2$ | watts | kg. | $C_R$ | watts |
| Upright commuting bike | 1.15 | 0.55 | 5.92 | 0.632 | 345 | 90 | 0.0060 | 53 |
| Road bike, touring position | 1.00 | 0.40 | 4.3 | 0.40 | 220 | 95 | 0.0045 | 38 |
| Racing bike, rider crouched, tight clothing | 0.88 | 0.36 | 3.9 | 0.32 | 176 | 81 | 0.0030 | 24 |
| Road bike + Zipper fairing | 0.52 | 0.55 | 5.92 | 0.29 | 157 | 85 | 0.0045 | 38 |
| Road bike + pneumatic Aeroshell + bottom skirt | 0.21 | 0.68 | 7.32 | 0.14 | 78.5 | 90 | 0.0045 | 40 |
| Unfaired LWB recumbent (Tour Easy) | 0.77 | 0.35 | 3.8 | 0.27 | 148 | 90 | 0.0045 | 40 |
| Faired LWB recumbent (Avatar Blubell) | 0.12 | 0.48 | 5.0 | 0.056 | 30.8 | 95 | 0.0045 | 42 |
| Vector faired recumbent tricycle, single | 0.11 | 0.42 | 4.56 | 0.047 | 25.8 | 105 | 0.0045 | 46 |
| Road bike in Kyle fairing | 0.10 | 0.71 | 7.64 | 0.071 | 39.0 | 90 | 0.0045 | 40 |
| "M5" faired low racer | 0.13 | 0.35 | 3.77 | 0.044 | 24.2 | 90 | 0.003 | 26 |
| "Flux" SWB, rear fairing | 0.55 | 0.35 | 3.77 | 0.194 | 107 | 90 | 0.004 | 35 |
| Moser bicycle | 0.51 | 0.42 | 4.52 | 0.214 | 118 | 80 | 0.003 | 24 |
| Radius "Peer Gynt" unfaired | 0.74 | 0.56 | 6.03 | 0.415 | 228 | 90 | 0.0045 | 40 |
| "Peer Gynt" + front fairing | 0.75 | 0.58 | 6.24 | 0.436 | 240 | 93 | 0.0045 | 41 |
| ATB (mountain bike) | 0.69 | 0.57 | 6.14 | 0.391 | 215 | 85 | 0.0060 | 50 |

[1] Data from various sources, including Gross, Kyle and Malewicki (1983), and Wilson (1997).

Compared with a golf ball, a bicyclist travels much slower but has a larger equivalent diameter, so the Reynolds number may be similar. A bicyclist using an upright posture may be considered for simplicity as a circular cylinder normal to the flow, a curve for which is shown in figure 5. If we take a cylinder diameter of 600 mm to represent an average person, and if we use a speed of 5 m/s, the Reynolds number is $2 \times 10^5$—below the "transition" region of about $4 \times 10^5$. Therefore there may be some advantage to wearing rough clothing for speeds in this region. Most bicyclists have become aware of the penalty of converting themselves into smooth but highly unstreamlined bodies by donning a wet-weather cape or poncho, which usually, and somewhat paradoxically, greatly increases the wind resistance without increasing the cross-sectional area. Perhaps some "trips" woven into the cape material would be beneficial. Even better would be some type of frame that would convert the cape into a low-drag shape. Sharp (1899) proposed this scheme in 1899, and capes with inflatable rims were for sale around that time.

Most everyday bicycling occurs in the Reynolds-number range of $1–4 \times 10^5$, and the reduction in air drag through the use of some form of practical low-drag shape as an enclosure or "fairing" can approach 90%. An even greater reduction in drag can be produced with special-purpose fairings for racing or setting speed records.

Low-drag shapes do not generally exhibit the sharp transition from high drag (separated flow) to low drag (attached flow) as the Reynolds number is increased. Rather, the point of transition of the boundary layer from laminar to turbulent tends to move upstream toward the leading edge of the body as the Reynolds number is increased. Thus, the drag coefficients for streamlined shapes (represented by an airship) given in figure 5 show a continuous fall as the Reynolds number is increased in the laminar-flow region, followed by a moderate rise to the fully turbulent conditions and then a continued fall.

The Reynolds numbers of streamlined fairings for human-powered vehicles lie in the interesting transition region between $1.5 \times 10^5$ and $1.5 \times 10^6$. The curves in figure 6, taken from Hoerner (1965), show that for a drag coefficient based on maximum cross-sectional (or frontal) area, the minimum drag coefficient is given by streamlined shapes with a length/(maximum thickness or diameter) ratio of about 4.

## Reducing the aerodynamic drag of bicycles

To reduce the wind-induced drag of a bicycle and rider, two alternatives are to reduce the frontal area of rider plus machine and/or to reduce the drag coefficient that the combined body presents to the air-stream. For years, bicyclists have adopted one or other of these possibilities, but only recently have there been concerted attempts at reducing frontal area and drag coefficient simultaneously. The results have been remarkable. A selection of interesting and typical data has been assembled in table 1 [3, 4]. The drag coefficients and the frontal areas are given in the first two columns, and the product of the two, $C_D{\cdot}A$, in the fourth column. Typical values for these three for an "upright commuting bike" are 1.15, 0.55 m$^2$, and 0.632 m$^2$. This bicycle, sometimes called "the British policeman's bicycle", and rider and this set of values are usually regarded as the "base case", to which improvements can be made.

An obvious improvement is for the rider to change position. A so-called "touring position" is used when riding a "road bike" (one with "dropped" handlebars) but with the hands on the top of the bars. This reduces the drag coefficient from 1.15 to 1.0 and the frontal area from 0.55 to 0.4 m$^2$, giving a reduction in $C_D{\cdot}A$ from 0.632 to 0.40 m$^2$. The fifth column of the table shows the power required at the driving wheel to overcome the aerodynamic drag at 10 m/s (22 mi/h). This is a speed at which aerodynamic drag is becoming dominant on unfaired bicycles. This fifth column shows immediately why ordinary people do not commute on upright bikes at 10 m/s: it requires 345 watts, approaching half a horsepower, just to overcome aerodynamic drag. The power into the pedals also has to supply losses in the transmission, normally small, and the rolling friction of the tires on the roadway, for which some typical data are given in the last three columns. The total would be over 400 watts, a level that NASA, testing "healthy men", found could be maintained for only one minute. Just making the switch to a road bike and using the touring position would lower the total power required (on level ground in calm wind conditions) to around 275 watts, and a nominally healthy male could keep this up for about 30 minutes, a typical commuting duration. (It would be very atypical to be able to commute for 30 minutes at constant speed, but if the typical male could do that, the distance would be 18 km, 11 mi.)

A further dramatic improvement occurs if the rider uses a racing bike (little different from the road bike, but we have specified a lighter weight and a frontal area that includes the effects of tight clothing and having the hands on the "full-drop" part of the handlebars; the rolling drag implies the use of light, supple, high-pressure tires). (Loose clothing can increase aerodynamic drag, at speeds of over 10 m/s, by 30%.) The drag coefficient goes down to 0.88 (mainly because the head is down in front of the rider's rounded back); the frontal area is 0.36 m$^2$, and $C_D{\cdot}A$ becomes 0.32. The power required to ride at 10 m/s is, including tire and transmission losses, about 210 watts, which even NASA's healthy man could keep up for almost an hour. People who ride such bikes are more likely to be "first-class athletes", who can be capable of riding at 10 m/s indefinitely, which might be translated as until the need for food, sleep or other demands of the body must be answered. (The one-hour standing-start record was set in 1996 for conventional racing bikes by Chris Boardman at 56.375 km, requiring an estimated average power output of over 400 watts.)

## Prone, supine and recumbent positions and bikes

The frontal area can be reduced below that required for a conventional racing bike only by adopting a changed pedaling position. Speed records have been won on bicycles designed for head-first face-down horizontal-body (prone) pedaling, and for feet-first face-up horizontal-body (supine) pedaling, in the strict forms of which a periscope or other viewing device (including TV) is needed; and for a wide variety of what is known as "recumbent" pedaling. The purists would say that fully recumbent pedaling is supine, and that strictly the position used by the riders of "recumbents" is in fact "semi-recumbent." However, this form of bicycle has become known in the English-speaking world as recumbent, "'bent" or "bent" (and in Europe as Liegerad or liegfiets). A well-known successful recumbent, the Tour Easy (from Easy Racers), is shown in table 1 as having a drag coefficient of 0.77, a frontal area of 0.35 m$^2$, and a $C_D{\cdot}A$ of 0.27 m$^2$, considerably lower than that of the racing bike with the rider in a painful crouch. Thereby lies a principal reason for the recumbent's growing popularity at the turn of the millennium: it can be simultaneously fast and comfortable. (These data may not be typical: also given in the table are measurements on a Radius "Peer Gynt" recumbent for which considerably higher drag values were measured.)

The drag of any HPV is greatly reduced if it is enclosed in a streamlined fairing. Paul van Valkenburgh developed Sharp's idea (mentioned above) in the "Aeroshell". Table 1 gives data for the use of this inflatable "suit" plus a skirt to extend the shape to close to the ground. A drag less than half that of the racing bicycle was attained.

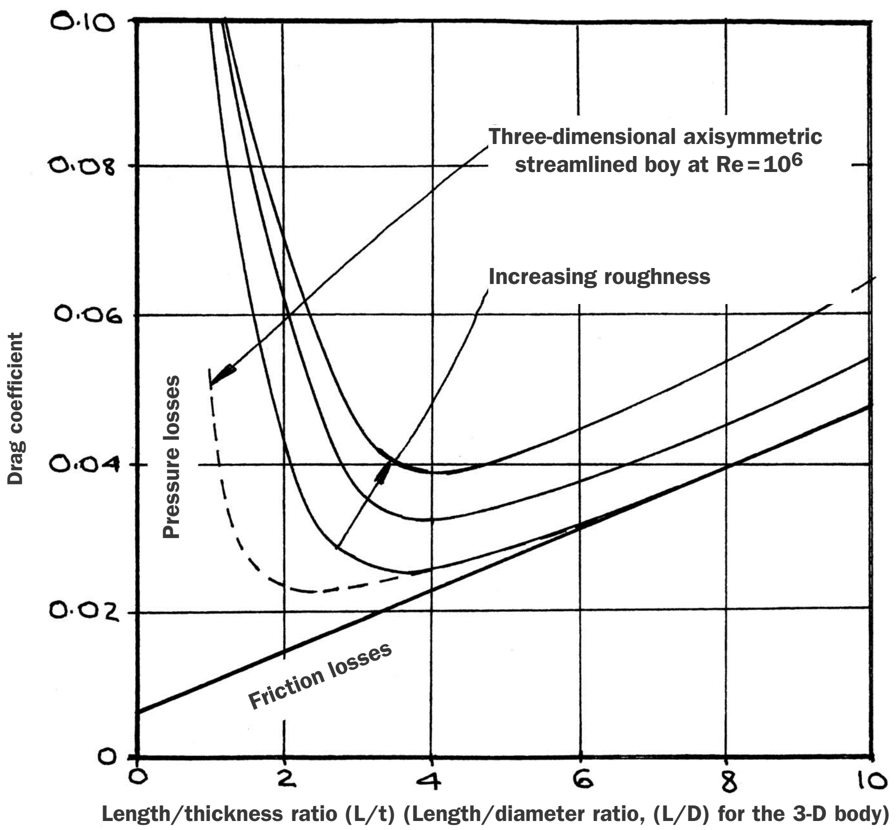


**Fig. 6. Optimum (L/t) of wing and strut sections and of one 3-D streamlined body (plotted from data from Hoerner [2] and other sources)**

## Unusual human-powered machines

In this chapter we aim to expand your experience, and perhaps make you want to use, or even design and make, some interesting human-powered devices other than bicycles. This aim has an obvious relationship to bicycling, which is an activity having a transportation component that can usually also be accomplished by the use of a motor-vehicle. People in the developed world who choose to bicycle generally do so for reasons connected with their own health and well-being and that of the region in which they live, and perhaps out of concern for the earth as a whole. There are rather similar, but far more limited, choices that such people can make for mowing grass and clearing snow, for example, and for recreational boating. The role of human power in the modern high-technology world has, alas, to be restricted. Only a very few enthusiasts bicycle across North America, Russia, Asia or Australia for pleasure. While we are engaged in some advocacy for human power, we are not recommending that human power should be used for such prodigious feats as bicycling across a continent, nor to clear snow from a supermarket parking lot, nor to cut the grass of a golf course. However, even in large countries like the USA, over half the daily "person-trips" by automobile are under 8 km, 5 mi, normally an easily-accomplished bicycling distance by most people in most weather conditions. Likewise, most lawns and driveways are of sizes that can easily be handled by human-powered devices. The past enthusiasm for reducing what has been called "back-breaking" labor through the incorporation of gasoline-engine- and electric-motor-powered devices has led to an almost total neglect of efforts to improve human-powered tools. In consequence, there is today an unfair competition between highly developed modern electric hedge clippers, for example, and manual shears that have not been sensibly improved for a hundred years. Perhaps we need a new series of Kremer prizes (which have been just for HP aircraft) for specified achievements in human-powered tools.

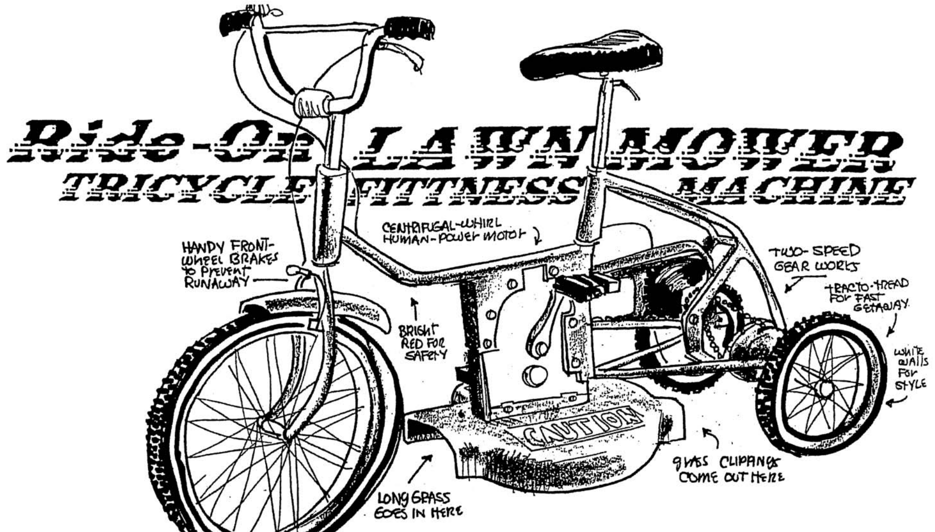


Figure 7. Vertical-axis commercially sold pedaled lawn mower

### Human-powered lawn-mowers and snow-removers

In the first two editions of *Bicycling Science* we had illustrations of Michael Shakespear's pedaled lawnmower. In view of the extremely limited budget and time he had available, it was beautifully designed and executed. His achievement might have inspired others. A commercial riding mower came on the market later using a vertical-axis high-speed rotary blade that, because of the power required for this type of cutter, made a slowly advancing cut of only about 300-mm width (fig. 7). However, it did cut long grass and weed stalks, often missed by reel-type mowers.

Another type that would cut long grass was sold in North America and probably elsewhere for much of the early part of the last century and is shown in figure 8.

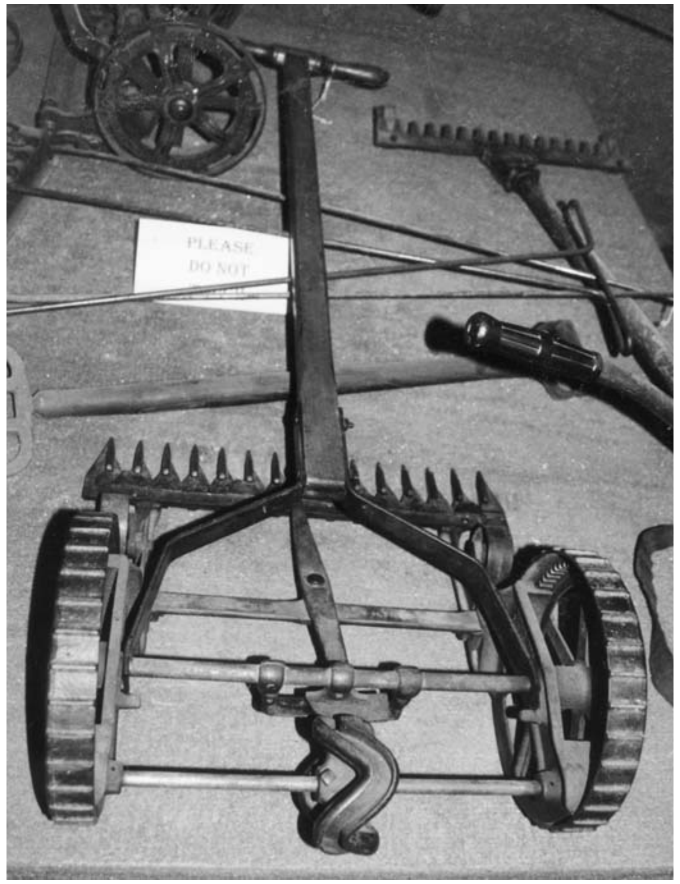


Figure 8. Sickle-bar push lawn-mower (National Agricultural Hall of Fame, Kansas)

A so-called "sickle-bar" or row of clippers in front of the wheels of a "push" mower was driven from a cylinder cam that would seem to have a high friction. This type of cutter has no intrinsic system of removing and collecting the clippings.

A compact and stylistic riding mower with a central reel was built by Chris Toen in the Netherlands.

The author has discussed riding mowers in *Pedal Power* (McCullagh 1977). He believes that the energy required to pedal a machine across soft ground (a lawn) is so high that the only way in which pedaling would be superior to pushing a mower would be for the pedaler to be either stationary or moving slowly, while the cutter, presumably light in weight, covers a considerable area.

Figure 10. The author's push snow-plough

### Snow removers

The use of snow shovels at the first snowfall of the winter always seems to produce reports of heart attacks. It is another example of a heavy task involving the use of the muscles of the arms and back, and of having the back bent uncomfortably. It would be better to use the big muscles of the legs and to have a more natural posture, which, combined, presumably would be less likely to over-strain the heart. It would be delightful to have a small lightweight device that, from leg operation alone, would scoop up a quantity of snow and project it in a desired direction, as one does with considerable effort using a snow shovel. Nothing like that has been on the market, or even in the patent literature, so far as can be learned from searches carried out by the author and his students. One favorite tool is shown in figure 10. This is an old "push-plough" bought by the author at a "garage sale." He made and installed a large fiberglass "blade" with a mild-steel cutting edge. He likes to demonstrate that, on the asphalt surface of his driveway (about 50 $m^2$) he can clear snow in about half the time taken by his neighbors with similar driveway areas, using their engine-powered snow-blowers.

We do, however, need better human-powered snow-removal devices, efficient, fun to use even for older and nonathletic people, and compact when stowed.

### A multi-human-powered land vehicle, the Thuner Trampelwurm

The Thuner Trampelwurm is a unique type of human-powered "road train" (fig. 11). Although other linked trains of HPVs exist, none is as radical as the Trampelwurm, a brainchild of the Swiss artist Albert Levice. Ten two-wheeled trailers, each for one person, are hooked up behind a long-wheelbase recumbent tricycle in such a way that they follow the leader almost perfectly—almost as if on rails defined by the path of the leading trike. It was a difficult task for a group of students led by Hansueli Feldmann at the Engineering College of the Kanton of Bern in Biel to come up with a usable system. They

Figure 11. The Thuner Trampelwurm

designed a good compromise with almost perfect tracking and enough stability to drive up to about 15 km/h without the train beginning to snake back and forth. Even so, hydraulic yaw dampers are required at the connecting links. A similar pitch-stability problem was solved by using the trailer units in pairs: each pair having one pinned and one sliding coupling. This also allows the train to be shortened easily, very handy if only a few people want to use it. Each unit has a seat and pedals or a linear drive or a rowing mechanism, as well as a roof made of canvas on a tubular frame.

Four complete vehicles were built by unemployed persons at the city of Thun in Switzerland, and extravagantly decorated by local school children. The city of Thun owns and operates three of the vehicles. A part-time staff of six people run the project, taking bookings and doing the frequent repairs necessary. Another ten people are engaged as drivers; the vehicles ply for customers in the pedestrian part of Thun and are available to be booked privately. Although as heavy as an automobile and as long as any legal road vehicle, the Trampelwurm can negotiate the most crowded and narrow pedestrian areas in safety and can also travel on the roads as long as they are not too steep. Parties enjoy the tricks of the drivers, like catching up with their train's own tail, forming a temporary human-powered merry-go-round, or diving into a particular steep narrow tunnel in roller-coaster fashion. Operating from April to November, the number of people transported per year is on average 5,700.

## Human-powered water vehicles

### Recreational and utility watercraft

### The Vél'eau 12

Vél'eau 12 is a human-powered boat with seats for twelve persons, six on each side facing one another, offset to allow for ten pedal drives (fig. 12, 13). These are connected to the longitudinal propulsion shaft under the floor. All drives except the helmsman's have freewheels, so the danger associated with multiple fixed pedals is removed. An arrangement of universal joints and a telescoping section allow the propulsion shaft—exiting at the uppermost point of the transom—to connect to the propeller/rudder unit in such a way that this can be steered almost 90 degrees to either side and also lift 90 degrees, for example in shallow water or for clearing the propeller. Internally, the propeller unit contains a simple untwisted chain drive with a step-up ratio of about four. The two-bladed propeller has a diameter of 550 mm and a pitch of 700 mm.

Vél'eau 12 is 12 m long and 1.3 m wide. The hull is hard-chine and made from 6-mm marine plywood glued and sealed with epoxy. Plastic hoops support a removable canvas roof with clear sides. There is also a leeboard to prevent excessive sideways drift in windy conditions. The complete craft weighs about 250 kg.

**Figures 12 and 13.** "Vél'Eau 12" HP boat

Vél'eau 12 is easily driven by as few as two persons. The all-day cruising speed is about 5 knots, with crews of four to ten average persons. Vél'eau 12 is owned by the French company Solartis (formerly Ecoinventions), which rents it out to groups that often take camping equipment for week-long trips, mainly on the river Saône.

## Human-powered vehicles in the future

To write about the future is, of course, risky. It is easy to review recent trends and to extrapolate. However, we will give some relevant data on bicycle usage and manufacture, with appropriate cautions on extrapolating them. We shall point out that, although we like to think of ourselves as free creatures, what we do is largely controlled by governmental actions, and that these actions are highly uncertain, even in democracies.

### Government regulations and incentives

A major component of national behavior comes from laws and regulations and on the degree to which these are enforced. While it could be stated that these laws and regulations in turn come from the people of their respective countries, the "law of unintended consequences" applies to laws themselves in addition to regulations and customs, and thereby shape communities in ways that they might not originally have foreseen.

Some examples are the following. In the nineteenth century in the U.S. the federal government saw an overwhelming need to connect the various parts of the country and to "open up the West" and it gave generous inducements to railroad companies to build lines. For this and many other reasons was born an era of "railroad barons" such as Cornelius Vanderbilt: people with great wealth and power. Oil was discovered, and "oil barons" such as John D. Rockefeller joined the ranks of America's multi-millionaires. The Sherman Anti-Trust Act became law in 1890 and the Interstate Commerce Commission (ICC) was given, to quote the Handlins (1975), "extensive rate-fixing authority [by 1910]. The courts became battlegrounds across which lawyers sallied to establish the boundaries between licit combinations and conspiracies in restraint of trade… litigation was a wholesome alternative to the overt violence and chicanery that had enlivened entrepreneurial contests in the 1870s.… While sometimes, as in the case of railroads and urban transit systems, those constraints [e.g. rate-fixing and rule-making] were so narrow as to stifle growth, in most industries entrepreneurs bore the burden lightly and even profited from it…". The coming of automobiles and the empires associated with them created conflicts. The ICC and other regulatory bodies seemed to have opposite effects on railroads and highways: railroads began losing money and merging or going out of business while truckers began taking over freight hauling, even over long distances along the same routes covered apparently more efficiently by the railroads. Similarly, differential taxation and regulation made it far less expensive for a family and even an individual to drive an automobile or to take a bus between two cities than to take a train, and passenger railroads have died out in the USA except when highly subsidized.

This may seem to be a topic that is unrelated to bicycling, but have patience! Economists show that trucks and automobiles are also subsidized, in fact subsidized to a far greater extent than are the few persisting passenger railroads. However, the subsidies are of a totally different character. Subsidies for passenger railroads and subway systems are tax monies that are handed over to the railroad managements. Subsidies for highway users are costs imposed on general taxpayers and on many others (for instance, the costs of highway maintenance, snow clearing, bridge repair, accident services, police, pollution costs, delay costs, urban-sprawl costs, and so on) that are not charged directly to highway users. It is politically very difficult to correct these anomalies, because lobbyists connected with all the powerful groups that would be affected are very active in advancing legislation favorable to the industries they represent, and vice versa. There are virtually no powerful lobbyists looking out for the interests of the weaker groups, including poor people, pedestrians, and bicyclists, who would benefit from the correction of anomalies and the promotion of fairness.

In summary, users of automobiles in particular are highly subsidized in the U.S., by an average for the quantifiable costs alone assessed by some economists as 67 cents per mile in 2002 money (or between $4,000 and $12,000 per automobile per year). Therefore the users of other forms of transportation, including urban bicyclists, are competing with this enormous motor-vehicle subsidy. In other countries with higher fuel and other taxes, the subsidies are lower than those in the USA, but they are still significant. And a fuel tax is a very crude method of recovering some of the "external costs" of using motor vehicles. To produce greater fairness in road use, three complementary forms of taxation are needed: electronically collected per-km road-use taxes, and parking taxes, both varying with place and time of day, in addition to fuel taxes. (Preferably, proposers of taxation should also stipulate the destination of the monies collected. It is the author's opinion that these taxes should be deposited in a trust fund that is reduced to near zero each month by a uniform distribution to all (at least to all adult local) citizens through a "negative" income tax, i.e., a refund or rebate. In this way, poor people would receive a guaranteed small income. Rich people would receive the same rebate income, but their additional expenditures would be likely to be higher than this rebate if they used automobiles.) The author has been advocating this policy so stridently since the early 1970s that his friends have called it "Wilsonomics." It is gradually coming to be accepted, even by economists. It has been picked up by Greenpeace Germany, and it may be incorporated into legislation there and possibly elsewhere. [It has been suggested many times in Switzerland, but not yet implemented, *Ed.*] A different approach with similar consequences has been proposed recently by Barnes (2001).

The vital relevance to our argument here is that most bicycling occurs in urban and suburban areas. These are also the locations where there is increasing traffic accompanied by gridlock and "road rage", apparently all over the world. If there were a gradual introduction or increase of all three forms of taxation, to an extent appropriate for each urban area, there would be a gradual reduction of motor-vehicle use, starting with those people whose use of motor-vehicles is a daily choice between two level-value alternatives, and who would happily decide not to drive if it were made a little less attractive.

There have been many movements in many countries to introduce road-use taxes, sometimes called “congestion taxes”, and there are now places where tolls on high-speed roads parallel to heavily used roads are collected electronically. However, the complexity of region-wide introduction of road-use taxes for a large nation or group of associated nations is so great that it seems likely that they will be first introduced comprehensively in an island nation and, if successful, spread rapidly to others.

Governments can also regulate. City centers, parks, and other recreational areas can be prohibited for motor vehicles. Highways can be declared off limits for bicyclists. There have been several campaigns in Asian countries to banish rickshaws and to restrict bicycles. In democracies, motor-vehicle and oil-producer lobbies are very powerful, and it is necessary that bicyclists have lobbyists to counteract what would otherwise be absolute power. “Power corrupts, and absolute power corrupts absolutely.”

The comments of Andrew Oswald (2000) on the alleged ruination of Britain’s universities are relevant to the bicycle situation. “These measures were the work of outwardly rational and plausible politicians. As with most mistakes in life, they did not happen because of outright malice. They were made by honest men and women with the best of muddled intentions. The problem was sheer mental sloth, plus an eye on short-term exchequer advantage, rather than on any appraisal of long-term costs and benefits….”

A reduction in the large subsidies to motor vehicles is the key to greatly increased use, coupled with fairer regulations for all classes of vehicles. However, forecasting the future use of bicycles and other human-powered vehicles is an impossible task, dependent on government actions that might be directed at one set of problems unrelated to bicycles, and might yet create unintended effects on bicycle usage. “The price of liberty is eternal vigilance.”

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Dave Wilson is the former editor of *Human Power*, co-author with Allan Abbott of the book *Human-powered vehicles*, and professor of mechanical engineering, emeritus, at MIT.

# Factors affecting performance in human powered vehicles: a biomechanical model

***Danny Too and Gerald E. Landwer***

## Abstract

There are a large number of biomechanical factors that affect cycling performance. These factors can often be grouped into one of three categories: (1) environmental factors, (2) internal biomechanical factors, and (3) external mechanical factors. The interaction of different factors within a category can be complex, but need to be examined and understood if more effective human-powered vehicles are to be developed. The purpose of this paper is two-fold: (1) to examine the factors in each category, their interactions, and how they affect performance in human-powered vehicles, and (2) to provide a biomechanical performance model for these factors.

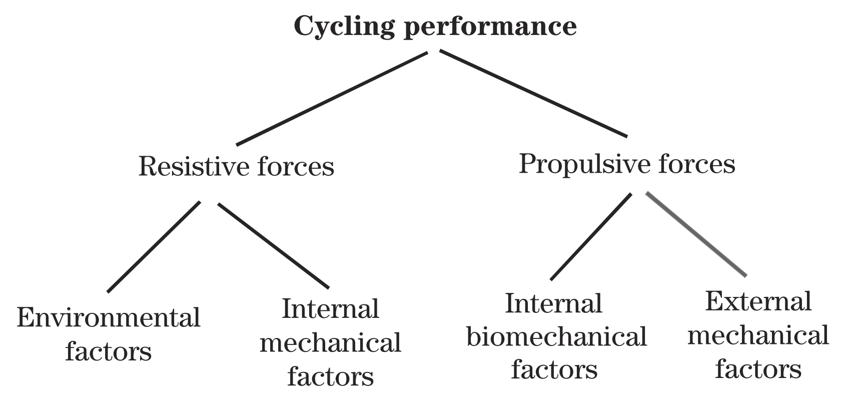

**Figure 1. Cycling performance**

## Introduction

Performance in land and water based human-powered vehicles are a function of the amount of propulsive forces produced versus the amount of resistive forces that need to be overcome. Greater production of propulsive forces with greater reduction of resistive force will result in greater performance in a human powered vehicle. Propulsive forces are often affected by internal biomechanical factors, external mechanical factors, and their resulting interactions, whereas resistive forces are often a function of environmental factors and internal mechanical forces (muscle frictional forces and viscosity; see fig. 1). Designers of human powered vehicles generally focus on how resistive forces can be minimized (as opposed to considering how propulsive forces might be maximized) because environmental factors are universal, more predictable, less complex, and independent of the interactions involved in maximizing and maintaining propulsive forces.

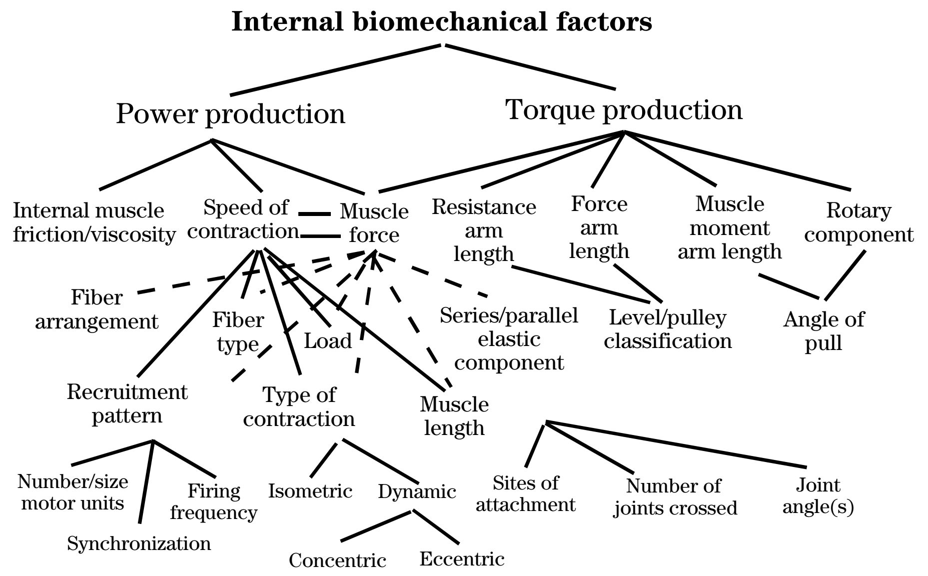

**Figure 3. Internal biomechanical factors**

## Environmental factors

Environmental factors such as gravity, friction, and air resistance are generally resistive forces that inhibit cycling performance on land. The extent that frictional forces or rolling resistance affect cycling performance is dependent on the type of terrain encountered; the smoothness/irregularities and hardness of the contact surfaces between the wheel and road; the cyclist/vehicle weight; the type of material of the wheel/tire and road surface, road texture; tire tread pattern, size, thickness, diameter and hardness (air pressure); deformation of the rolling wheel, and vehicle velocity (2, 6; see fig. 2).

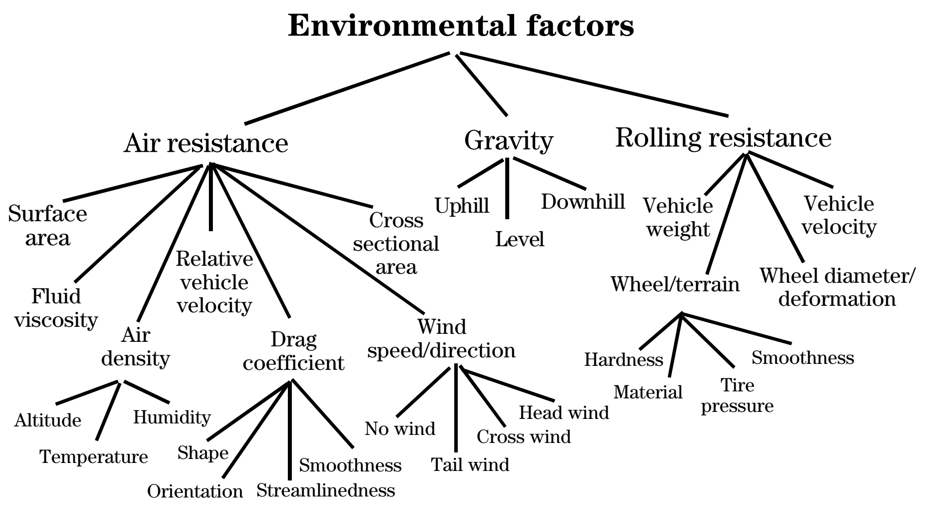

**Figure 2. Environmental factors**

Aerodynamic drag is affected by factors such as: air density (altitude, humidity, and temperature), vehicle velocity, cyclist-vehicle cross-sectional area perpendicular to the direction of motion, and the drag coefficient (shape, streamlineness, orientation, and smoothness of the rider and bicycle). Changes in air density by cycling at high altitudes, or changes in the drag coefficient (by modifying the vehicle shape or size, or the use of aerodynamics suits, fairing, solid disc wheels, etc.) can significantly alter cycling speed, time, and performance (5, 6, 7).

## Internal biomechanical factors

Internal biomechanical variables affecting propulsive force and cycling performance involve factors related to force/torque development and power production as depicted by the proceeding biomechanics performance model (see fig. 3).

These are factors not often understood or considered by designers of human powered vehicles because of the complexity of their interactions. Manipulation of these factors can modify and alter the effective muscle force/torque/power generated and transmitted to the vehicle. These factors include: position of initial and final muscle length, change in muscle length, muscle moment arm lengths, force arm length, load imposed on muscle, resistance arm length, direction/line/type of force (resultant, stabilizing, rotary, dislocating), point of application, joint angles, muscle angle of pull, single or multi-joint muscles, muscle fiber type and arrangement, type and number of lever/pulley systems involved, type of muscular contraction (concentric, isometric, eccentric), speed of contraction, muscle recruitment patterns (firing frequency, synchronization, number and sequence of motor units involved), contribution of series and parallel elastic components, internal frictional forces and viscosity within the muscle; and differences in segmental limb lengths and limb ratios (2, 4, 8). Changes and interactions occurring in the internal biomechanical variables resulting in propulsive force are often the result of manipulations of external mechanical factors.

## External mechanical factors

External mechanical factors involve constraints imposed upon a cyclist by the structure of the vehicle and how power is transmitted to the vehicle. These factors include: the seat-to-pedal distance; seat tube angle; seat height; pedal crank arm length; handlebar height, length, and position; cycling body position, orientation, and joint configuration; foot-pedal position; chainwheel size and shape (circular versus elliptical); use of cams; gear ratios; the wheel size, mass, diameter and inertial properties; and losses in power transmission due to friction.

Manipulating these variables will alter joint angle position, joint angle ranges, muscle length, resistance load, muscle mechanical advantage, and/or the ability to produce force/torque/power. Therefore the resulting propulsive force will be a function of the interaction between the internal biomechanical factors with the external mechanical factors in developing force, torque, and power for propulsion (1, 2, 3, 8). However, complexity is further increased when one must consider how changes in the shape and structure of a human powered vehicle (from manipulation of the external mechanical factors) not only affect propulsive forces, but also how it affects the type of resistive forces encountered from the environmental factors, and the resulting interaction between these forces.

It is beyond the scope of this paper to examine and review the existing literature, regarding how changes in external mechanical factors (seat-to-pedal distance; seat tube angle, crank arm length, body position, orientation, and joint configuration) interact with the internal biomechanical factors to affect force and power production in human powered vehicles. However, a future paper will examine the biomechanical and physiological variables involved in muscle force production and provide information as to why and how changes in external mechanical factors interact with these variables to affect force production.

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## E. Eugene Larrabee: a remembrance

E. Eugene Larrabee died on 11 January 2003 in Mt. Vernon, NY, at the age of 82.

Gene Larrabee was a professor at MIT and made key contributions to the science and technology of aircraft and road vehicles. He is known to readers of *Human Power* for his work in propeller and windmill design.

Following are the remembrances of several who knew Gene Larrabee.

### Mark Drela

His [Eugene's] design methods could be performed easily with a hand calculator or a spreadsheet. They were usable even by lay engineers with no specialization in aerodynamics, which made them very popular with aircraft and boat homebuilders, hobbyists, and wind power manufacturers, in addition to their expected use by the light aircraft industry. As for Larrabee's personal style, he had a tendency to interject an amusing and relevant historical aviation anecdote into almost every conversation.

### Theo Schmidt

After reading his article in *Scientific American*, Gene Larrabee inspired me to design my own propellers—paradoxically not by using his method, which I could not understand, but by devising my own. However without his help and encouragement I would never have started. The resulting "amateur" program "PropSim" is since being used by many hobbyists, and around one hundred propellers have been made [using PropSim]. Gene and his wife, Christine, visited us in Switzerland when I was still living with my parents. Gene took a keen interest in the Tour de Sol, a race for solar and solar human-powered vehicles, which was taking place at the time of his visit.

### Dave Wilson

When I came on the MIT faculty in 1966 Gene was teaching a course on motor-vehicle design in Aero. When he retired he went to California to teach at Northrop University and remained active as a consultant. I valued his contributions to human-powered aircraft and also found him to be modest about what he did. He wrote that he had simply taken the theory of German aerodynamicist Albert Betz† to produce a propeller design system that he called "minimum induced drag." It seemed to give efficiencies of around 90%.

The MIT team was trying to win the Kremer prize for the first crossing of the English channel, and their rival was the MacCready "Gossamer Albatross" team that had won the first Kremer prize, for a figure-of-eight flight, with its "Gossamer Condor". Paul MacCready asked if we could provide him with a propeller. Instead, the "Chrysalis" team, or Larrabee's students working on the propeller, designed a special propeller for their rivals. We were told that with their old propeller having an efficiency of about 70%, pilot Bryan Allen could stay aloft only ten minutes before he was exhausted. With the minimum induced drag propeller he stayed up for over an hour on his first flight with it, and had to be ordered down because his ground crew (most members of which bicycled below the plane) were tired out. There was thus no way he could cross the Channel (which took him almost three hours) without the minimum induced drag propeller. I think that this action for its rivals reflects much credit on the MIT team and probably on Gene Larrabee, although I don't know who made the decision to be so helpful to the Californians."

### Paul MacCready

We became connected when we both attended a meeting, probably the winter of 1978–79. While there, I became acquainted with Eugene's work on rational propeller design, and found he was rapidly putting his ideas into design practice. I enlisted his aid, and that of his very helpful students, in coming up with a design for the propeller used with the *Gossamer Albatross*. The propeller data Gene sent me needed careful construction. I believe it produced about 87% prop efficiency. The design by Gene and his crew was essential to the success of the *Gossamer Albatross*. However, there were many other essentials also, and we could not publicize all the credits.

At least his contribution was mentioned in my paper included in the Society of Experimental Test Pilots 1979 Report, *Twenty-Third Symposium Proceedings*, Sept. 25–29, 1979. The presentation states: "We subsequently made numerous improvements, the most significant being to utilize a propeller design by Professor Larrabee of the Massachusetts Institute of Technology. That propeller powered the 1 hour 9 minute flight at Harper Dry Lake in late April 1979, after which Bryan Allen said he could have easily flown 3 more hours."

### Sarah Wright

Born in Marlborough, Mass., in 1920, Larrabee received the B.S. in mechanical engineering from Worcester Polytechnic Institute in 1942. During World War II he worked on aircraft stability and control problems at the Curtiss Wright Corp.

Larrabee began teaching at MIT in 1946 while still a graduate student, and received the S.M. in aeronautics in 1948. He retired in 1982.

A founding member of the Tech Model Aircrafters, he was a popular and accessible figure among students, colleagues and hobbyists who shared his enthusiasm for flight. Larrabee was also known for his designs for research apparatus, having contributed to the designs of the Student Wind Tunnel used at MIT from 1947–1961, an innovative wall balance for testing small automobile models, and a research windmill.

In addition to his wife Christine (Rogan), Larrabee is survived by a daughter, Rose, of Mt. Vernon, NY, and a son, Paul, of Brookline, MA.

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## Minimum induced loss wings and propellers for human-powered vehicles

***by E. Eugene Larrabee (May 1985)***

Fortunately the human power plant is long on strategy if short on performance. For a human being to fly by his or her own strength in the air, or over water on submerged hydrofoils, the most efficient wings and propellers must be used. Generally these will have large spans or diameters in order to minimise kinetic energy left in the wake, and very small air-foil (or hydro-foil) chords in order to minimize skin friction. In addition, lifting loads or propelling thrusts should be distributed spanwise or radially in such a way that the wake kinetic energy content is minimized. This is the case when the residual wake velocities caused by the steady production of lift or thrust have a geometrically simple character.

These distributions are called minimum induced loss loadings because they are sometimes calculated with the aid of mathematical ideas originally developed for analysis of magnetic fields induced by electrically conducting wires, which are important in electrodynamics. The loaded wing or propeller blade produces a moving vortex, bound to its surface and proportional to the local load, which has a certain spanwise or radial gradient. It must fall to zero at the wing or propeller tips and also at the propeller shaft. By Stokes' law, spanwise or radial gradients of "bound" vorticity give rise to free vortex sheets made up of trailing vortices. The velocity field "induced" by these vortex arrays is mathematically analogous to the magnetic field induced by geometrically similar arrays of current carrying wires, and may be calculated by the Biot-Savart law. Wing and propeller loadings optimised to minimise the "induced losses" were first described by Ludwig Prandtl, Max Munk, Albert Betz and others of the Kaiser Wilhelm Institute for Flow Research at Goettingen, Germany, during and shortly after World War I. During the 1920s and 1930s, this knowledge was widely disseminated among theoretical aerodynamicists but imperfectly communicated to aeronautical engineers, many of whom continued to design and build airplanes by trial and error.

As is often the case, these optimal solutions for spanwise lift and radial thrust distribution have a mathematically simple character which is easy to write down, and even easy to remember. This document summarizes essential relations for minimum induced loss wings and propellers, which should help recent arrivals in the human powered vehicle field to build well-proportioned designs with efficiency insured from the start. They still apply to engine powered airplanes, of course.

**Figure 1.**

The vortex theory of airfoils is due to Nicolai Yegerovitch Joukowsky (sometimes transliterated Zhukovskii) and Wilhelm Kutta, and dates from 1911. Joukowsky devised the conformal transformation which maps the flow about a circular cylinder with bound vorticity into the corresponding flow about a lifting airfoil. Kutta showed that if the bound vorticity is adjusted to place the aft stagnation point in the flow about the cylinder at the singular point (where x = -a, y = 0), the transformed flow about the airfoil will leave the trailing edge smoothly, and this determines airfoil lift. The lifting "circulation", or vorticity, in physical airfoil flow is due to the difference in vorticity between the upper and lower surface boundary layers. All modern airfoil theory contains the Kutta-Joukowsky results as a special case.

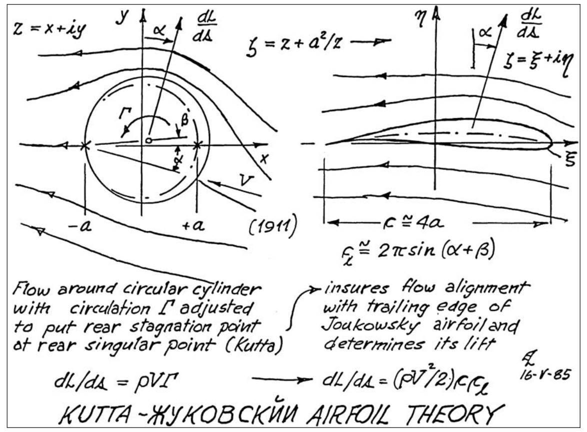


**Figure 2**

Since the lift, and hence the bound vorticity, must go to zero at the tips of a monoplane wing, there must be a certain spanwise gradient of lift which minimizes the kinetic energy of trailing vorticity comprising the vortex wake. Max Munk showed (in 1916 ?) that an elliptic lift distribution does this by creating a spanwise uniform downwash velocity of the nascent trailing vortex sheet. Albert Betz later showed that such a trailing vortex sheet would wind itself up into two "tip vortices" with no change of energy level. The spanwise constant induced angle of attack for elliptic loading (which is optimum) may be written

$\alpha_i = w/V = (\text{lift})/\pi\cdot(\rho\cdot V^2/2)\cdot b^2$

or $= C_L/\pi\cdot(AR)$

where $C_L$ is the wing lift coefficient, $(\text{lift}/S)(\rho\cdot V^2/2)$, AR is the aspect ratio equal to $b^2/S$, and S is the wing area.

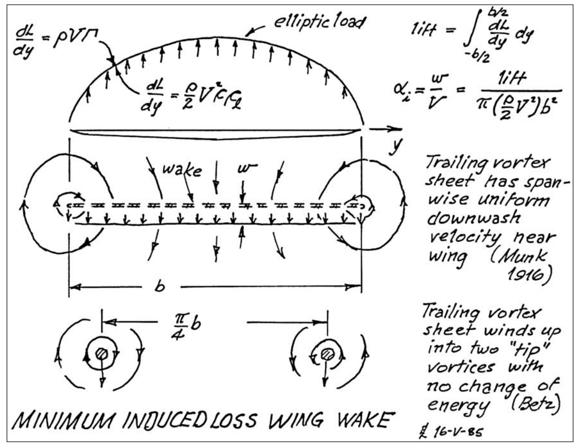


**Figure 3**

The large span of a human-powered airplane wing, 29 m (95.14 ft), is made necessary by the slow flight speed, 7 m/s, and the low density of air, 1.225 kg/cubic meter at 760 mm Hg and 15 degrees Celsius. If the wing profile drag coefficient is taken to be twice the turbulent skin friction coefficient as given by von Karman,

$0.242/\sqrt{C_F} = \log_{10}(C_F\cdot Re)$, the power to fly the loaded wing is about 155 W.

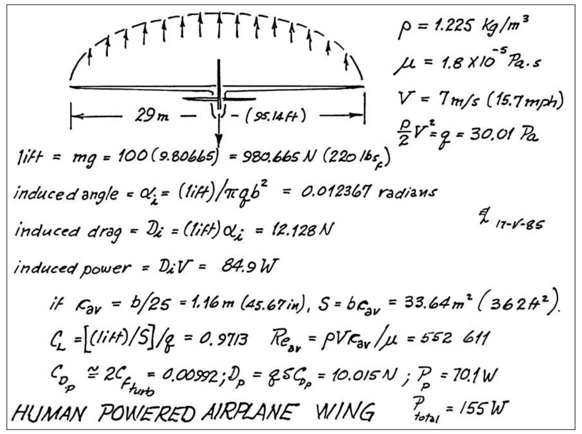


**Figure 4**

The much smaller 1.5 m (59 in) span of a human powered hydrofoil wing is made possible by the much higher density of water, 1000 kg per cubic meter. Since the hydrofoil operates close to the surface, the amount of fluid it can influence is halved and the induced angle is doubled. The power to fly such a loaded hydrofoil wing is about 195 W at a speed of 6 m/s under the same assumptions as the human-powered airplane wing.

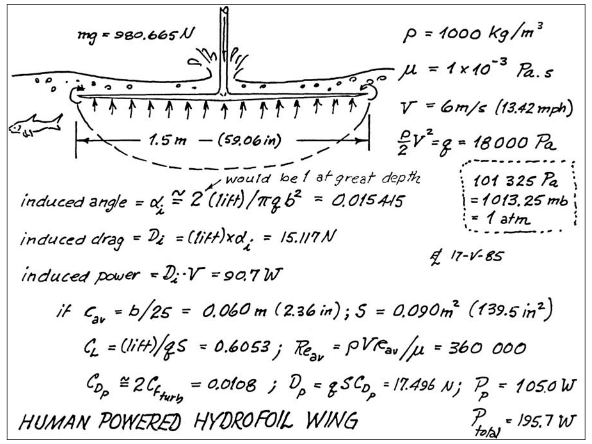


**Figure 5.**

The concept of propeller "slip" is as old as the steamboat screw propeller. The difference between geometric pitch and effective pitch was first accounted for by Prof. J. M. W. Rankine (the prototypical Scotch engineering professor) and W. Froude, who showed that the propeller thrust must produce an increase in slipstream velocity, half of which is realised at the propeller disc.

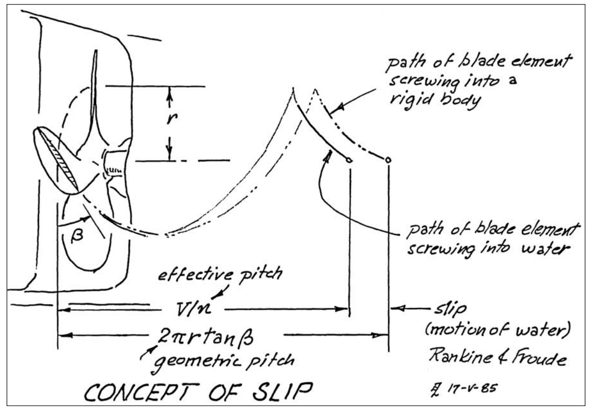


**Figure 6**

Albert Betz showed in 1919 that the slipstream velocity behind a thrusting propeller should give rise to a radially constant "displacement" velocity of its trailing vortex sheets, analogous to the spanwise constant downwash velocity behind an elliptically loaded wing. He wrote (translated): "The flow behind a screw with minimum energy loss is as if the path traversed by each blade (a helicoidal surface) became rigid, and displaced itself rearward with a certain velocity, or turned itself about the screw axis with a certain angular velocity." The misleading idea here is the statement that the helicoidal vortex sheets should move as rigid bodies. The correct interpretation is given in the figure.

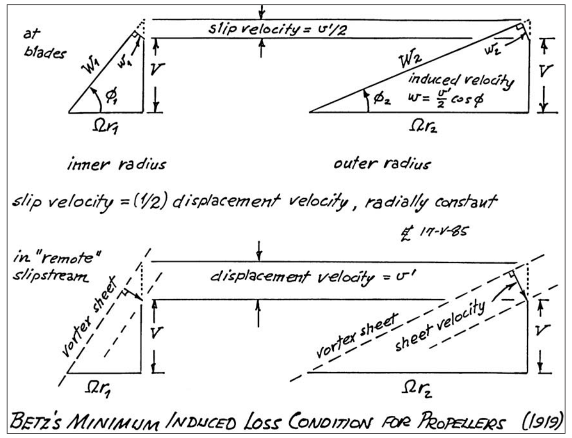


**Figure 7**

Just as an elliptic bound vorticity distribution gives rise to a constant downwash velocity behind a wing, so certain radial bound vorticity distributions give rise to slipstream vortex sheet motion which satisfies the Betz condition behind propellers. The bound vorticity distributions are functions of the advance ratio (or inverse tip speed ratio) and the number of blades. The dimensionless bound circulation G (for Goldstein) is also approximately the ratio of average axial slipstream velocity at a given radius to the displacement velocity. To minimize the slipstream kinetic energy (or induced loss) for a given thrust, airspeed, and diameter, the tip speed ratio and the number of blades should be increased, thereby making the slipstream more uniform.

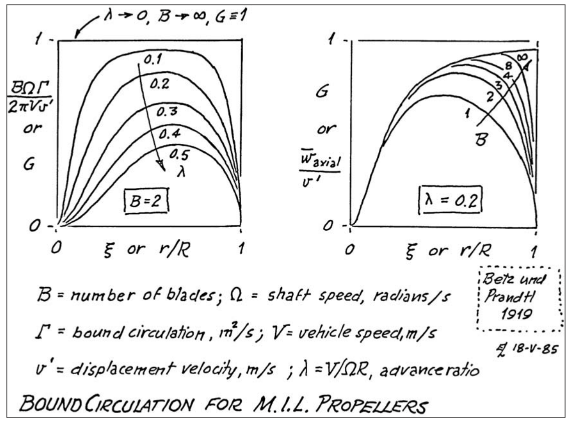
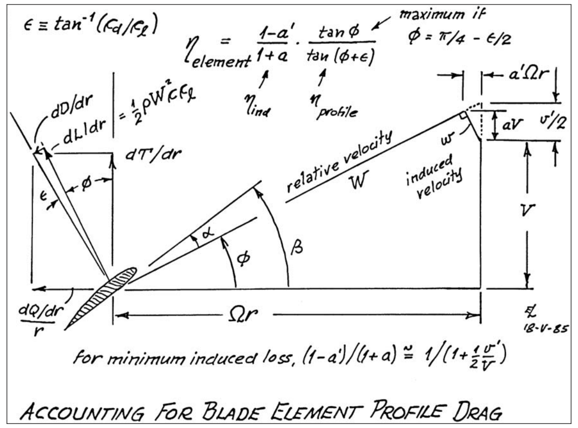


**Figure 8**

Just as a wing has profile drag, so propellers have profile losses. The profile efficiency of a propeller blade element is $\eta_{profile} = \tan\phi/\tan(\phi+\varepsilon)$ where $\phi$ is the helix angle of the blade element relative velocity W, accounting for the induced velocity w. In order to minimize profile losses of a propeller, the most heavily loaded portions near 80% radius should operate at $\phi = \pi/4 - \varepsilon/2$, and the blade number should be reduced to increase the blade chord Reynolds number, thereby reducing ε, the "glide angle", equal to the arctangent of airfoil section $C_d/C_l$. The conditions for reducing profile losses are in conflict with reducing induced losses.



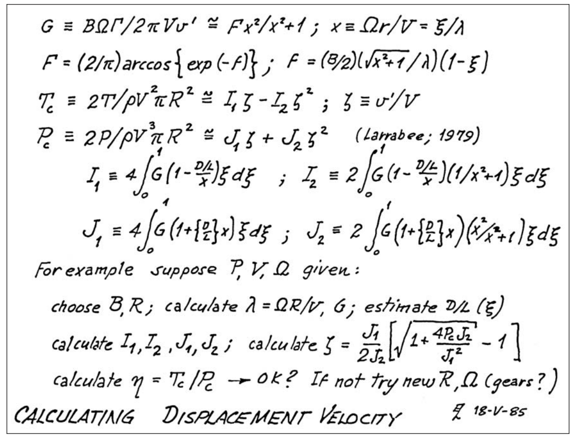


**Figure 9**

The thrust and power loadings of a minimum induced loss propeller may be written as quadratic functions of the displacement velocity and four loading integrals which can be evaluated numerically and account for wake geometry and radial glide number distribution. Once the displacement velocity has been found, the efficiency can be predicted. If satisfactory, the propeller geometry can then be determined. The dimensionless bound circulation function G is here calculated by an approximation due to Prandtl.

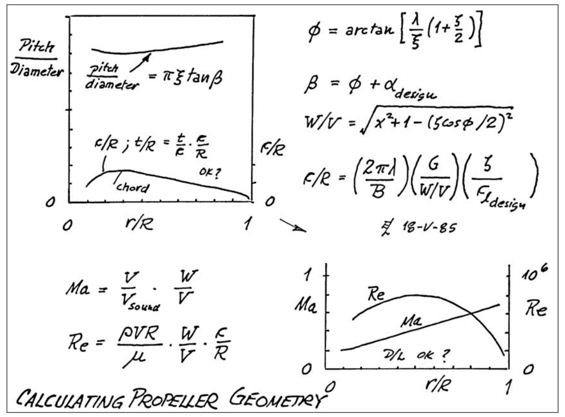


**Figure 10**

The geometry of a minimum induced loss propeller is completely defined as soon as its displacement velocity, corresponding to a specific thrust or power loading, has been calculated. The associated radial variations of blade chord Reynolds number and Mach number should be calculated to see if they are consistent with the radial variation of glide number (section drag/lift ratio) used to calculate the loading integrals.

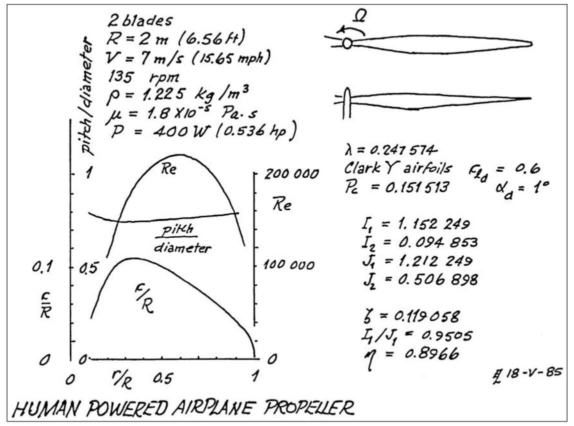


**Figure 11**

These are results of a propeller design calculation for a human powered airplane. The design power of 400 W is more than expected for level flight to insure efficiency during the climb. The Clark Y airfoils yield a lift coefficient of 0.5 at alpha equal zero degrees, measured with respect to the flat under surface. Note that specification of a design lift coefficient of 0.6, corresponding to an angle of attack of 1 degree, produces a slightly non-uniform pitch/diameter ratio. The calculated chords inboard of 30% radius are too small because of errors in the Prandtl approximate bound circulation, and should be increased appreciably, both for this reason, and also for structural integrity.

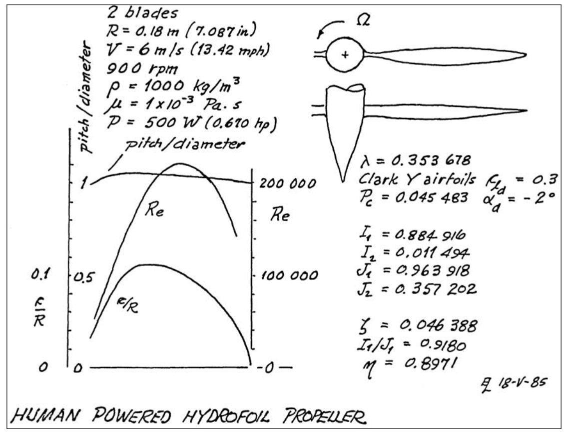


**Figure 12**

These are results for a similar design calculation for a human powered hydrofoil propeller. The small diameter of 360 mm (14.17 in) is made possible by the high density of water. The high shaft speed of 900 rpm is necessary to make the tip speed an appropriate multiple of vehicle speed with this small diameter. The low design lift coefficient of 0.3 is chosen to increase blade chord Reynolds number and minimise cavitation.

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# Various efficiencies of a human-powered flywheel motor

**J. P. Modak and A. R. Bapat**

[*Editor's note*: This article is based on a lengthy scientific paper "Formulation of generalised experimental models and their optimisation for transverse force exerted on the pedal and various efficiencies of a human-powered flywheel motor" received by *Human Power*. For reasons of space some sections have been replaced by editor's summaries.]

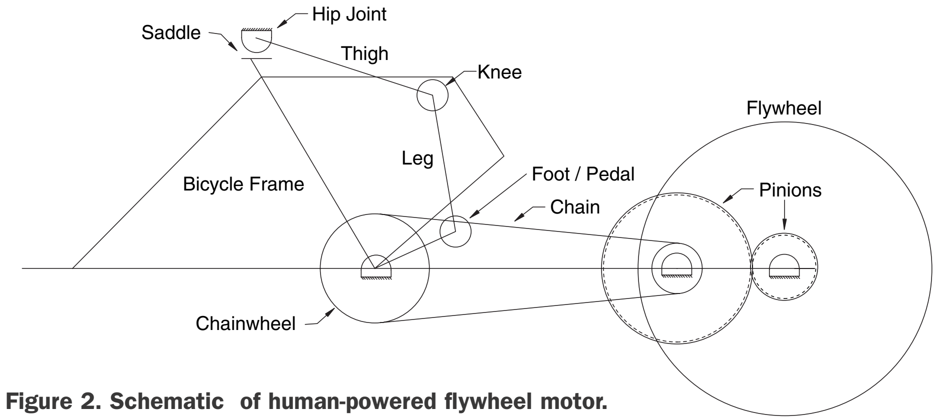


**Figure 2. Schematic of human-powered flywheel motor.**

## Abstract

In the recent past a human-powered process machine has been developed for brick making, wood turning, clothes washing and drying and earthenpot making (Modak 1982 and 1998, Askhedkar 1994). The machine consists of a human-powered flywheel motor using a bicycle-drive mechanism with speed-increasing gearing and a flywheel, which drive the process unit though a clutch and torque-increasing gearing (Gupta 1997). The operator puts energy into the flywheel at a convenient power level for about one minute. After enough energy is stored, pedaling is stopped and the energy in the flywheel is made available to the process unit. Suitable duties are those requiring up to 2 kW and up to 10 kJ in total energy at each application. In a previous investigation by the authors (Modak and Bapat 1994), a generalised experimental model for the human-powered flywheel motor was established for some responses of the system. The present investigation focuses on some additional responses. The generalised experimental models established in this research are amply validated by experimental findings. [*Editor's note*: the process unit has been previously described in *Human Power* (Modak & Moghe 1998) including drawings and pictures. This article covers the human-powered flywheel motor.]

## Background of present work

During 1979–99, Modak (1982, 1994, 1997, 1998, and n.d.) developed a human-powered brick-making machine for manufacturing bricks out of a mix consisting of lime, fly-ash and sand. In this machine human power is the main energy source. The machine described in figure 1 consists of a pedaled flywheel with a speed-increasing transmission (abbreviated as Human-Powered Flywheel Motor, or HPFM), a transmission unit (spiral-jaw clutch and torque-increasing transmission), and the process unit consisting of an auger, a cone and a die. Although the system was developed essentially on the basis of intuition and past general experience, it proved to be functionally feasible and economically viable. This concept was also tried on a winnower (for removing food grain shells), a wood strip cutting machine, and a blacksmith hammer as developed by the Center of Science for villages in Wardha, India. This is the outcome of one project sponsored by the Department of Science and Technology of the Government of India during 1995–1998.

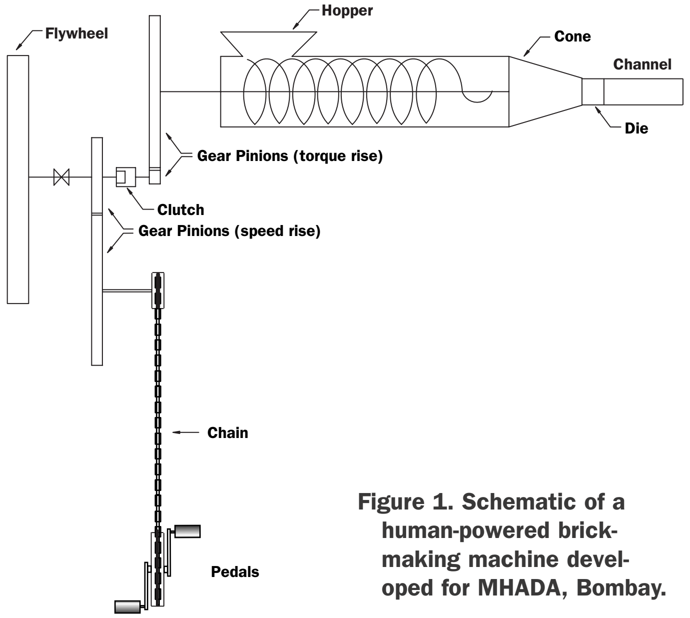


**Figure 1. Schematic of a human-powered brick-making machine developed for MHADA, Bombay.**

## Scope of present research

As an extension of earlier mathematical models (Modak & Bapat 1994), some more models are formulated for the response variables of the energy unit, such as the transverse force exerted on the pedal, the crank, pedal, and foot positions with respect to the frame, the pedal and flywheel energies. This paper essentially reports on experimentation which involves describing and varying independent variables, the method of measuring the response variables, the procedure of experimentation, data collection, presentation, and analysis, concluding with a qualitative logical analysis for the optimisation of the models.

## Experimentation

### Independent variables

G is the gear-ratio between the gear pinions at the flywheel. This is varied between 1.14 and 4; there are five steps. There is further fixed ratio of 1.9 given by the chain drive. Thus the total ratio from the pedals to the flywheel can be varied between 2.2 and 7.6.

I is the flywheel's inertia. This can be varied between about 0.26 and $3.5\,\mathrm{kg\,m^2}$ by fitting different flywheels, also in five steps.

R indicates the mechanical energy input by the rider during one minute's pedaling time. Twelve male riders in an age group of 20–22 years and of slim stature were chosen for the experiments. Each rider accelerated the flywheel for about one minute, subjecting himself to a comfortable maximum-exertion level. The load torque required to be overcome on the flywheel shaft is $I \cdot \alpha$, where $\alpha$ is the average angular acceleration during the pedaling duration of one minute. The load torque to be overcome on the pedals is therefore $G \cdot I \cdot \alpha$. The total air exhaled during experimentation was recorded by a specially-designed and fabricated spirometer (Bapat and Pote 1994). The specialty of measuring the exhaled air with respect to time is an improvement over the earlier investigation (Modak and Bapat 1994). The total (physiological) energy input by the rider is estimated from the exhaled air collected in the spirometer and the corresponding oxygen intake.

[*Editor's note*: Part of the paper (omitted here) compares the kinematic properties of the standard upright bicycle geometry with several modified geometries: One called the "quick-return-ratio=1" drive gives smaller than usual knee angles and a more even force distribution around a complete pedal-crank revolution. A further mechanism is called the double-lever inversion, and the last is an elliptical chainwheel having its length twice its breadth. In all these, the rider's thigh and lower leg together with the pedal-crank are considered parts of a four-bar linkage, with foot action not included in the mathematical model. Tangential or pulling forces possible by "ankling" and/or using pedal clips are thus not part of the model. This predicts that the modified mechanisms are kinematically better than the standard configuration by factors of up to 38%. These predictions are, however, not validated by the subsequent experiments, where the standard geometry is found best in terms of efficiency. However, the test persons seemed to prefer the configuration called "double-lever inversion" for accelerating the flywheel.]

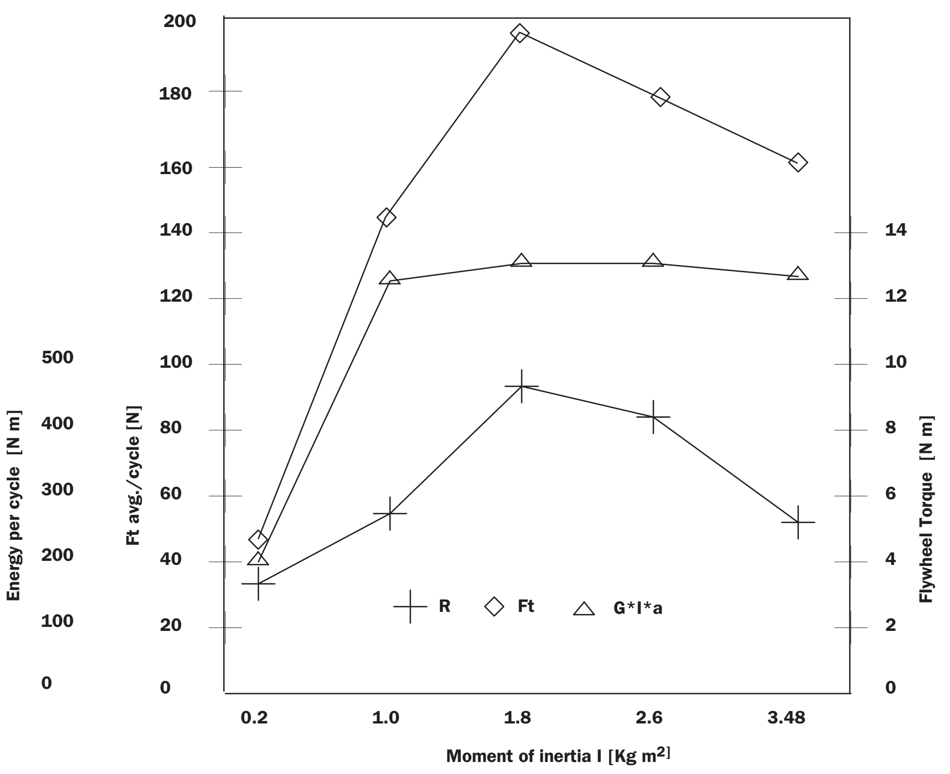
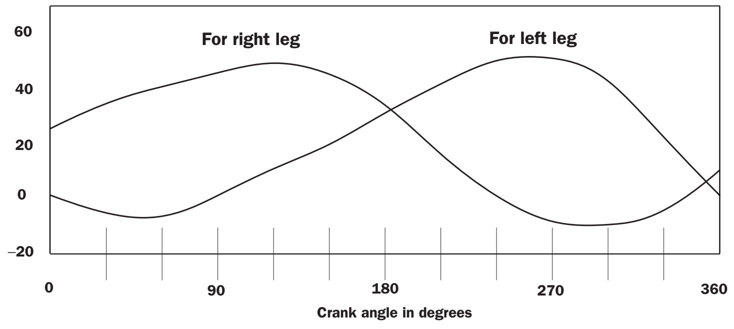


**Figure 4. Ft, R, and flywheel load torque vs. I, averaged over 1 min.**

**Dependent variables**

Ft, the transverse force exerted on the crank, is measured using strain gauges which are mounted midway on the cranks. The instantaneous strain values are stored in a computer memory for further processing. The crank angle is measured digitally by using a circular ring having equally spaced drilled holes and a photoelectric sensor which measures the interruptions of the light beam as the ring rotates. The pedal energy is estimated in terms of the pedal force Ft, the circumference of the pedal rotation, and the number of rotations of the pedal during the period of pedaling. The flywheel energy is estimated in terms of I (the flywheel's moment of inertia), and the terminal flywheel speed which is measured by a tachometer. An X-T plotter gives the graph plot of the instantaneous flywheel speed during the period of pedaling.



Avgerage force = 38.8 N
Pedal energy (approx. 1 minute) = 2616 Nm

**Figure 3. Instantaneous Ft vs. crank angle**

## Conduct of experiment

Experiments were conducted while varying I and G independently. All twelve riders operated the system for every combination of I and G and the values of the corresponding independent and dependent variables were recorded.

Figure 3 describes the variation of instantaneous Ft vs. crank angle for both the legs for one cycle of operation of the pedal crank. (Here the result is the average of 3 riders from the 12, chosen at random.) The total average Ft is 38.8 N and during one minute an energy of 2616 Nm is accumulated, thus the average power here is about 44 W. I is given as 0.225 kg m$^2$ and G is given as 1.5.

Figure 4 presents the measurements of some physical quantities versus I (average values from the 12 riders). These are the energy input R, the traverse pedal force Ft and the flywheel load torque, all averaged over the pedaling duration of one minute. G is given as 2.0.

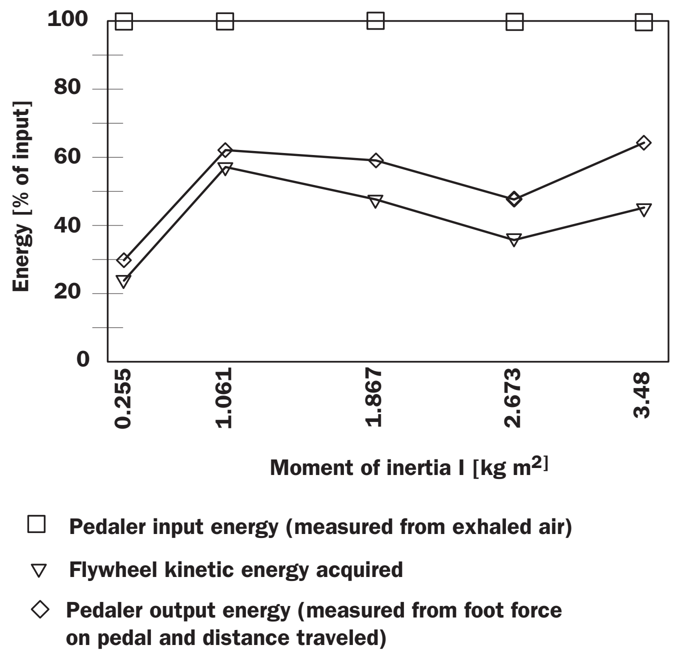


**Figure 5. Energy efficiencies measured at the end of 1 min. pedalling duration**

Figure 5 presents the variations of pedal energy and flywheel energy at the end of the one-minute pedaling duration versus I, given as percentage of the input energy (average values from the 12 riders). G is given as 2.0.

[*Editor's note*: Two sections "Analysis of results" and "Corroboration of generalised experimental models" (not given here) detail the best combination of variables to use for a specified objective function, e.g., if the objective is to minimise pedal force Ft, the smallest available values for I and G are to be used. However in terms of efficiency, as seen in figure 7, the combination I=1.06 and G=3.8 is optimal. In terms of maximum power, as seen in figure 4, the same combination very nearly gives the maximum flywheel torque, and hence maximum flywheel power (neglecting flywheel losses). The generalised mathematical model however gives different optima for efficiency when the variable in question is I, and the authors conclude that for this case more experimental evidence is needed in order to understand the relationships.]

## Conclusion

There exists a considerable similarity in this investigation and of previous investigators (Sargeant *et al* 1978) regarding the pattern of transverse force Ft exerted on the pedal at every instant during the cycle of each leg. There has been some difference in the pattern of Ft for both the legs during the rise of Ft compared with the previous investigations. This needs to be confirmed by additional research. It is not desirable to keep the flywheel moment of inertia I in the range of 1.4 to 2.4 kg m$^2$. This is because during this variation of I all the three parameters R, Ft and $G \cdot I \cdot \alpha$ have fairly large values.

In view of keeping internal human-body energy losses and frictional energy losses at a minimum, it is necessary to keep G at 3.8 and I at 1.06 kg m$^2$, however lowering G to 2.85 or even 2.17 may result in a reasonable compromise between the intensity of taxing muscles and incurring considerable internal physiological energy loss in the human body.

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## About the authors

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